Sketch map showing the distribution of some of the better-known glaciers of North America
Southern limit of Pleistocene ice sheet indicated by a heavy broken line.

GLACIERS

OF

NORTH AMERICA

A READING LESSON FOR STUDENTS OF GEOGRAPHY AND GEOLOGY

BY

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TO THE READER.

UNTIL within the past few years, nearly all current knowledge of glaciers was based on the study of those of the Alps. Practically all theories of the origin, growth, motion, etc., of glaciers were inspired from the same source. An enlargement of the field of study, however, has shown not only that glaciers of the same type as those of Switzerland exist in many other lands, but in numerous instances are larger and present greater diversity; and besides, additional types or "genera" have been discovered that are not represented in Europe or in fact on any of the three continents of the Eastern Hemisphere.

As geological and geographical explorations have been extended, it has been found that North America is not only a favorable field for the growth of these twin sciences, but in many ways furnishes the best example of continental development that has as yet been studied. Strange as it may appear in the face of the overshadowing popular interest that centers in the glaciers of the Alps, North America offers more favorable conditions for the study of existing glaciers and of the records of ancient ice sheets than any other continent. Of each of the three leading types of glaciers thus far reorganized, namely, the alpine, piedmont, and continental, North America furnishes magnificent examples. In fact there is no other continent, except the little known region about the South Pole, in which other than the alpine type of glaciers exist. Of alpine glaciers representatives occur in North America in abundance and in great variety, ranging from the "pocket editions" about the summits of the High Sierra, California, to the magnificent Seward glacier, Alaska, the largest river of ice flowing from a mountain group that has yet been discovered. Of piedmont glaciers, the type specimen, so to speak, and the only one of the class yet explored, is the great ice sheet that intervenes between

Mount St. Elias and the Pacific, known as the Malaspina glacier. The still larger continental glaciers — of the nature of the ice sheet that formerly covered the northern half of North America, and the smaller sheet beneath which northwestern Europe was once buried — are represented in the Northern Hemisphere at the present time by a single example in Greenland.

The magnificence of the field for glacial study in North America has only been appreciated within recent years, and is still unrecognized outside of a limited circle of special students. By gathering in the book before you the information now available concerning North American glaciers, it has been my aim not only to report the present condition in this country of an important branch of geological and geographical enquiry, but to make you familiar with glacial phenomena in general and stimulate a thirst for fresh explorations and renewed study along an almost untrodden path.

From what I have seen personally of the glaciers of the United States and Canada, and from glimpses obtained in previous years of those of Switzerland and New Zealand, as well as from all that I have read concerning the ice fields of other lands, I think I can affirm, without fear of contradiction, that southern Alaska and adjacent portions of Canada offer one of the most promising fields for glacial study that can be found. I shall be more than repaid for the labor expended in writing this little book if it leads even indirectly to a renewal of the explorations now barely begun in that instructive, highly picturesque, and most attractive region.

ISRAEL C. RUSSELL.

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I am especially indebted to the Director of the U.S. Geological Survey for the electrotypes used in reproducing the illustrations forming Plates 3, 4, 5, 17, 18, 19, and 20. Other acknowledgments for similar favors will be made in advance.

I. C. R.

GLACIERS OF NORTH AMERICA.

CHAPTER I.

INTRODUCTION.

It may be said of glaciers in general that they are bodies of ice formed by the accumulation and consolidation of snow in regions where the snowfall for a series of years is in excess of the amount melted and that they flow to regions where waste exceeds supply.

While a typical glacier is easily recognized, and there is no dissent from what is commonly understood by the name applied to bodies of flowing ice, yet the limitations of the term are indefinite. A type may be chosen, as the well-known Mer de Glace, Switzerland, for example, in which most of the characteristics of glaciers are exhibited. Other ice bodies are known, however, equally deserving to be classed as glaciers, that are markedly different from such a type. The vast ice sheet of Greenland exhibits a great departure from the ice streams of Switzerland in certain features; while the small ice bodies in the Sierra Nevada, California, present minor variations in other characteristics. In both of these illustrations, and in many others equally at variance with the type chosen, the term glacier is as appropriate as in the case of the ice stream on the border of the Vale of Chamounix.

The difficulties in determining the limitations of the term *glacier* may be illustrated by the use of the word *river*. When does a stream cease to be a brook, or a creek, or even a lake, since many lakes are but expansions of streams, and reach the dignity of a river? In a similar way, it is difficult to decide when an accumulation of snow acquires sufficient of the characteristics of a typical glacier to be included in the same class; or again, when a glacier loses motion and becomes a stagnant ice body, when it shall cease to be known by the title it earned when it was an avenue of ice drainage.

In instances where the conditions are indefinite or peculiar, only an arbitrary decision can, perhaps, be reached; but usually the presence or absence of a number of the commonly recognized characteristics of typical glaciers is sufficiently pronounced to exclude controversy.

Leading Characteristics of Glaciers.

Mode of Accumulation. — The formation of glaciers in any region depends primarily on climatic conditions. When the climate is such that the amount of snow falling for a term of years is in excess of the amount melted, evaporated, or blown away, perennial snow banks are formed, the more deeply buried portions of which become compacted into ice. The change from snow to ice is known to result from pressure and from partial melting and refreezing. Many observations have been made which show that normal glaciers have a characteristic flowing motion. The material of which they are composed is drained from regions of accumulation in much the same manner as rivers drain areas where the rainfall exceeds evaporation. This process of ice drainage relieves areas of heavy snowfall from their burdens, and prevents indefinite accumulation.

Three Types of Glaciers. — For convenience of reference the glaciers now known may be arranged in three classes, namely, *alpine*, *piedmont*, and *continental*. These three classes are not always distinct and clearly separable, but typical examples of each may be selected that are well characterized, and differ in essential features from typical examples of each of the other classes. In each group there are conspicuous variations which suggest minor or more specific subdivisions.

Of the three great classes referred to above, the most widely known is the alpine type, which derives its name from the mountains of central Europe, where it was first studied. Alpine glaciers occur about high peaks and on the summits and flanks of mountain ranges in many parts of the world, but reach their most perfect development in temperate regions. The Himalayas, the Alps, the mountains of Scandinavia, the Southern Alps of New Zealand, the Cordilleras, etc., furnish well-known examples. Glaciers of this type originate as a rule in amphitheatres and cirques, partially surrounded by lofty peaks and overshadowing precipices, and flow through rugged valleys leading from them as winding ice rivers which carry the excess of snow falling on the mountains to

lower regions, where a higher mean annual temperature causes it to melt. They are essentially streams of ice, formed usually by the union of many branches, and end abruptly when the drainage changes from a solid to a liquid form.

Glaciers of the piedmont type are formed where alpine glaciers leave the rugged defiles through which they flow and expand and unite on an adjacent plain. They may be considered as analogous to lakes, for the reason that they are fed by tributary ice streams. The influx of ice is counterbalanced by melting, especially from the surface and borders of the partially stagnant mass. The characteristics of glaciers of this type are foreshadowed when individual alpine glaciers leave a high-grade gorge and expand in a lateral valley or on a plain. The expanded terminus of Davidson glacier, on the border of Lynn canal, Alaska, illustrates what may be taken as the first step toward the formation of a piedmont glacier. The semicircular or delta-like ice foot of the Rhone glacier, Switzerland, where it spreads out at the head of the Rhone valley, is a more widely known, although a comparatively diminutive example of the same character. If one fancies a score or more glaciers of the Davidson and Rhone type, uniting on a plain and forming a single confluent plateau of ice many square miles in area, he will appreciate the leading characteristics of the ice sheets termed piedmont glaciers.

A type of the piedmont glacier, and the only one of the class thus far described, is Malaspina glacier, Alaska, situated at the southern base of Mount St. Elias and neighboring mountains, from which it is nourished by many ice streams. This magnificent ice sheet covers an area of 1500 square miles, and is from 1000 to 1500 feet thick. West of Malaspina glacier, and occupying a plain intervening between high mountains and the sea, is another piedmont glacier, known as Bering glacier, which is of the same general character as its companion, but has not been explored.

Ice bodies of the third class, as their name implies, are of vast extent and may even cover entire continents. Existing examples are confined to Greenland and to Antarctic regions. Others that have now vanished, left unmistakable records over large portions of northeastern North America and northwestern Europe. The principal characteristics of continental glaciers are their vast extent, their comparatively level surfaces, and the prolongation of portions of their borders into lobes and even into well-defined streams, where the topographic and other conditions are favorable.

On comparing the three classes of glaciers just enumerated, one finds that alpine glaciers, when well developed, appear as trunk streams formed by the union of many branches. They usually flow through narrow valleys from higher to lower regions, and end abruptly in precipitous walls of ice or expand at their extremities and terminate with low frontal slopes, according to local conditions. In many ways they are analogous to rivers. Piedmont glaciers receive many tributaries of the alpine type, are not confined by rocky walls, and do not have the well-defined stream-like flow exhibited by glaciers descending narrow valleys. They are only moderately lobed, do not send out well-defined branches, and are in part stagnant ice masses. Their nearest counterparts in ordinary water drainage, as already mentioned, are found in lakes fed by mountain streams. Continental glaciers are without tributaries, their broad surfaces forming the necessary gathering-ground for snow accumulation. Their margins may be strongly lobed, or even send out well-defined tongues of ice, but the area of ice extending beyond the margins of the central snow field is in existing examples comparatively small.

Each of the three types of glaciers here enumerated is represented in North America, and their characteristics and distribution will be described in the following chapters.

Névé and Glacier Proper. — Glaciers of the alpine type, and in a less marked way those of the continental type, have their surfaces divided into two portions, a névé or snow region above, and an ice portion below. The lower portion has no specific name, but is frequently designated as the "glacier proper." The line of demarcation is the *snow line*, *i.e.* the lowest limit of perennial snow. As compacted ice occurs also directly beneath the névé from which it is formed, this division of a glacier into two portions applies only to the surface. Moreover, the position of the dividing line is subject to secular variations. At times, possibly for many consecutive years, in the case of small glaciers, the snow may completely cover the true ice, so that one might walk over the accumulation and easily mistake it for the snows of a single winter, and be led to conclude that it was not entitled to be considered as a member of the great family of glaciers.

The névé is composed of stratified granular snow which is white or grayish white in color. The snow on high mountains is apt to be exceedingly fine, light, and dry when first formed; but by partial melting and refreezing it acquires a coarse, granular texture, much like compacted hail,

and also becomes consolidated and hard. The surface of the névé is many times so softened by the warmth between summer storms, that a thin crust of ice is formed when the temperature is again lowered. This crust is buried beneath the next succeeding snowfall and remains in the growing deposit as a thin stratum of ice. Névés are almost entirely free from stones or dirt, although even on the highest mountains, the dust borne from naked cliffs is widely spread over their surfaces and diminishes their brilliancy. This general dust-covering is frequently not noticeable until some really clean snow surface is brought in contrast with it. When a lake on the névé is drained and leaves a fresh surface of dazzling whiteness, the surrounding area frequently shows a gray tint by contrast, thus revealing the presence of dust which has been sprinkled over it. Sometimes the covering of dust, especially on the lower portions of the névés of alpine glaciers, is sufficiently pronounced to form a definite division plane when buried by subsequent snowfalls. Illustrations of such an occurrence may frequently be seen in the walls of fissures. In the great open fissures or crevasses that break the névés in the region about Mount St. Elias, a dozen more or less distinct strata separated by bands of blue ice, a fraction of an inch thick, or by still more conspicuous dust-stained layers, may be frequently counted. In some instances the layers of granular snow are fully fifty feet thick, even after having passed from the light, mealy consistency of freshly fallen snow to the much more compact condition of the granular névé snow, thus indicating the abundance of the snowfall in the regions where glaciers have their birth. The surfaces of névés are renewed many times during the year by fresh snow. Stones and dirt falling on them from surrounding cliffs, or swept down by avalanches from tributary slopes, are buried from sight and enclosed in the growing deposits.

Below the snow line, the true glacier, composed of compact ice, makes its appearance at the surface. The horizontal stratification so well marked in the névé is nearly or quite obliterated, but the ice takes on a characteristic banded structure, due to alternation of thin sheets of clear, blue ice with sheets of vesicular, white ice. As has been shown by laboratory experiments as well as observations on glaciers themselves, this peculiar banded or ribboned structure is caused, in part at least, by pressure, and is analogous to the slaty cleavage observable in certain rocks. At the lower extremities of glaciers in many instances the banded structure is obscure, or perhaps entirely obliterated, and the ice presents a coarse, granular appearance not unlike the grain of crystallized marble. As will be

explained, this "glacier grain" is not confined to the extremities of glaciers, but has been recognized throughout the extent of the glaciers proper.

The ice below the snow line is frequently dirt-stained and more or less completely covered with angular stones and large rock masses. This superficial covering is so general on many glaciers that from a distance no traces of ice can be seen, and they appear as dark and barren as a newly plowed field. In a general view of a snow-covered mountain range the two surface divisions of the glaciers on its sides are usually distinctly shown by contrast in color. The higher or névé portions are white and glistening, while the lower portions either reveal the blue tint of compact ice or are dark with earth and stones.

The débris that falls on a névé from bordering cliffs, and the dust blown over its surface, sink into the soft snow, principally on account of the absorption of heat owing to their dark color, and are buried by later snow storms. As the névé becomes consolidated and acquires motion, this débris is carried along within its mass. In the region below the snow-line, however, where the annual melting exceeds the annual snowfall, the surface of the ice is liquefied, and foreign substances previously buried become concentrated at the surface. The tendency of the névé is to bury foreign objects, and of the glacier proper to concentrate them at the surface. For this reason the lower and consequently the more wasted portion of a glacier is the more thoroughly dirt-covered.

Moraines. — All of the débris carried by glaciers may be designated in general as morainal material. When arranged in certain more or less definite ways it is known under specific names. When distributed along either margin of a glacier it forms *lateral moraines*. When two glaciers unite, the right lateral moraine of one of the branches joins the left lateral moraine of its companion, thus forming a *medial moraine* in the central portion of the compound glacier below the junction. When a trunk glacier is formed by the union of several branches, as is frequently the case, the number of parallel lines of débris on its surface is correspondingly increased, being always one less than the number of well-defined branches that unite to form the compound stream. This nomenclature will be better understood by referring to the following ideal sketch map of the surface of an alpine glacier, formed by the union of four tributaries. The moraines on the surface of the ice are shown by dots and the mountain slopes by sketch contours.

The débris carried to the end of the glacier and deposited about its extremity, in some cases forms a crescent-shaped ridge, known as a *terminal moraine.* Similar moraines about the margin of piedmont and continental glaciers are usually designated as *frontal moraines;* when two

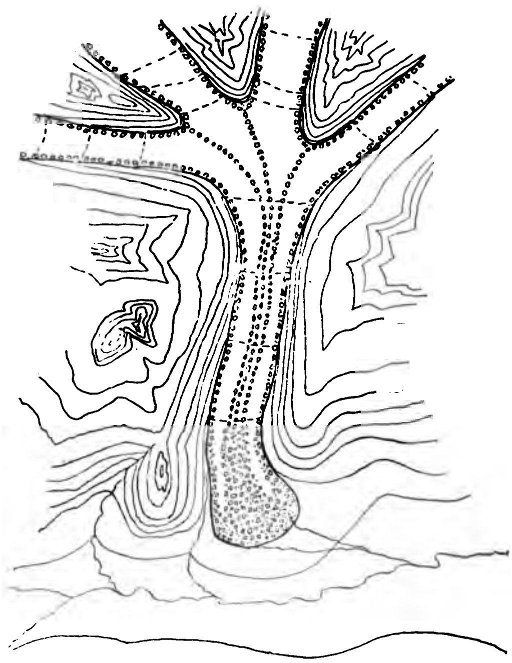


FIG. 1.—IDEAL SKETCH MAP OF AN ALPINE GLACIER, SHOWING LATERAL, MEDIAL, AND TERMINAL MORAINES.

lobes on the outer margin of such glaciers unite, the débris deposited along the line of junction forms *interlobate moraines.* Moraines are subglacial, englacial, or superglacial according to their position.

Other somewhat technical terms used to designate various modifications of morainal deposit will be explained in treating of glacial records.

Crevasses.—Moving ice masses, especially when flowing over rough surfaces or through rugged valleys, are subjected to stresses which cause them to break and fissures to open. Such open fissures were termed *crevasses* by Swiss mountaineers, long before the attention of scientific men had been called to them. The name has been adopted by glacialists as a general term for the gaping fissures that so frequently break the

surfaces of moving ice masses. Crevasses occur both in névés and in true glacial ice, and present varying characteristics which have led to a somewhat specific classification.

The snow fields at the heads of alpine glaciers are frequently traversed by fissures several hundred feet long and varying in width up to 50 feet or more. They are widest in the central portion, and taper gradually to mere cracks at their extremities, which are frequently curved in opposite directions. Even the greatest crevasses are at first simple or compound fractures, too narrow to allow one to insert the thinnest knife blade, and slowly open in the course of weeks or months. This widening of crevasses, especially in névés, is due to the stretching of the material that they traverse. It is frequently stated that ice, though plastic under pressure, yields to tension only by rupture. The slow opening of crevasses by the widening of their central portions, certainly indicates, however, that ice, when subjected to slowly acting tension, does stretch to some extent without fracture.

As stated above, crevasses begin as narrow cracks and gradually widen. While camping on the broad névés in the Mount St. Elias region, my attention was frequently called to the formation of these breaks in the ice. On one occasion, while sleeping in a tent far out on the névé of the Agassiz glacier, I was wakened several times during the night by rumbling sounds accompanied by sharp crashes, which seemed to proceed from the ice immediately beneath our tents. With each crash the ice trembled and vibrated as if an earthquake wave had passed through it. The sounds came so suddenly and were so startling that some of my party who were not familiar with the behavior of glaciers, rushed from the tent in considerable alarm, fearing that a crevasse was about to yawn beneath them. In the morning we found that a crack in the ice, several rods in length but without appreciable width, had formed immediately in front of our tents.

The walls of crevasses in névé regions are of the most exquisite turquoise blue, the color deepening below the surface until it seems almost black. The only color in nature that rivals the blue of glacial ice, is seen when one looks down into the unfathomable sea. The sides of crevasses are frequently hung with icicles, forming rank on rank of glittering pendants, and fretted and embossed in the most beautiful manner with snow wreaths, and partially roofed with curtain-like cornices of snow. These details are wrought in silvery white, or in innumerable shades of blue with suggestions of emerald tints. When the sunlight

enters the great chasms, their walls seem encrusted with iridescent jewels. The still waters with which many of the gulfs are partially filled, reflect every detail of their crystal walls and make their depth seem infinite. No dream of fairy caverns ever exceeded the beauty of these mysterious crypts of the vast cathedral-like amphitheatres of the silent mountains.

Encircling the upper borders of the névé in most snow-filled amphitheatres, there is a great crevasse or a series of nearly parallel and intersecting fractures that differ in certain ways from the crevasses formed lower down. The most rapid motion in a névé probably occurs deep below the surface, where the pressure is greatest and the ice compact. The light snow forming the surface of the névé is carried bodily forward by the flow of the ice on which it rests; this together with the general settling of the newer and more incoherent snow causes it to break away from the surrounding cliffs. Great open fissures are thus formed, which border the upper margin of the névé and separate it from the rocks above in such a manner, in many instances, as to offer an impassable obstacle. These breaks frequently mark the boundary between snow work and rock-climbing, and are known as *bergschrunds*, or mountain crevasses. Breaks of this character are among the very first to form when an amphitheatre becomes snow-filled, and continue to appear at the same localities as the glacier advances in age. They occur close to the bordering cliffs but leave portions of the névé, frequently several rods broad, still clinging to the rocks. A bergschrund, in the majority of instances, is of the nature of a fault. The snow left attached to the rocks and forming the upper margin of the crevasse stands higher than the opposite margin of the fracture. The snow forming the thrown block, has been affected by a downward movement, and also by a horizontal movement which opened the fracture. In observed instances, the vertical displacement is from a few inches to fifty or sixty feet or more; and the horizontal movement shown by the breadth of the crevasse, frequently from fifty to seventy-five feet. At times compound, or step faults, as a geologist would call them, are formed and two or more nearly parallel crevasses break the surface. In winter these breaks are filled and a new layer is added to the surface of the névé, but during the succeeding spring they form again in about the same position as the year previous.

In the breaks encircling the head of a névé, the rock beneath the snow left clinging to the mountain is usually exposed and becomes greatly shattered by frost and changes of temperature. The blocks thus loosened

are plucked out the succeeding year, when another crevasse forms in the same locality. It is thought by some students of topography that the waste from these exposed surfaces leads to the growth of amphitheatres and *cirques* and explains many of the peculiarities in the relief of glaciated mountains.

When a glacier descends a precipice it may become broken and fall in detached blocks, thus forming veritable ice cascades; but the fragments unite again at the base of the cliffs and become reconsolidated, and the ice flows on as a continuous stream. At other times the descent is completely covered with ice so shattered as to be impassable, and presents all degrees of diversity between ice cascades and ice rapids. The places of steep descent in the floor of a névé frequently lead to the breaking of the snow and ice into cubical blocks of all dimensions up to hundreds of feet in diameter, which bear a striking resemblance to towers and other architectural forms, and add most attractive features to the scenery of glacier-covered regions. During night marches on the glaciers of Alaska, the writer could scarcely put aside the idea that these shadowy forms partially illuminated by the northern twilight, were in reality the ruins of marble temples. In the lower portions of glaciers, where the ice is more solid and where surface melting is more rapid, the steep descents are marked by spires and pinnacles having extremely rugged and angular forms, separated by profound crevasses. These true ice falls are much more rugged and much more difficult to traverse than similar descents in the névé, and are seldom accessible even to the most experienced mountain climbers.

When a glacier passes over a moderate inequality in its bed, it is fractured so as to form crescent-shaped fissures which are widest just below the obstruction and gradually close as the slowly moving stream flows on. In passing over such obstructions the surface of a glacier, especially in the névé region, sometimes rises so as to have a backward slope. Instances of this nature have been observed in the neighborhood of Mount St. Elias. Marginal crevasses are formed on the sides of well-defined glaciers, owing to the friction on the sides and the more rapid flow of the central portion. These breaks trend up stream at angles of approximately 40°, and are broadest at the shore. When the banks of an ice stream are of snow and ice, counterparts of the marginal crevasses are formed in them and trend down stream, and are practically continuous with the breaks in the margin of the glacier itself. The marginal crevasses in the glacier and the similar breaks in the adjacent bank,

however, are separated by a band of shattered snow sometimes several rods broad, which sharply defines the margin of the current. These crevassed banks of snow and ice are common in the St. Elias region, and have been described by the writer.[1]

In the case of glaciers that expand on leaving narrow valleys, stresses are produced in other directions than in the cases cited above, and longitudinal or more or less regularly radiating breaks are produced. A well-known instance of this nature is furnished by Rhone glacier.

It may be judged from this brief sketch that the conditions leading to the fracture of moving ice masses are exceedingly varied and produce diverse results. The series of more regularly arranged fractures, to which special attention has been directed, are united by other and less easily explained breaks, so that the detail of the surface of an ice stream, especially when modified by melting, becomes at times wonderfully complex. It is only by selecting isolated and well-defined instances for study that the laws governing the behavior of ice under the varied stresses produced in flowing through irregular valleys and over rough surfaces can be at all understood.

The ice of glaciers is also broken along planes more or less inclined to their surfaces. Movement takes place along these breaks, and produces thrusts, analogous to the over-thrusts, or under-thrusts, sometimes seen in rocks that have been folded and broken. In fact, the counterpart of many of the structural features observed in rocks, such as faults, folds, joints, contortions, etc., may be observed in the ice of glaciers.

Surface Features. — Owing to the presence of crevasses and to unequal melting, the surfaces of glaciers are frequently exceedingly rough and irregular. Foreign matter resting on the ice, when sufficiently thick not to be warmed through by the sun's heat in a single day, protects the ice beneath, while adjacent surfaces not so protected are lowered by melting. Blocks of stone thus shelter the ice beneath and remain on pillars or pedestals as the surrounding surface is lowered. A group of such "glacier tables," as they are called, is shown on page 44. These were observed by the writer on a small glacier on the High Sierra of California, and present a fair idea of the character of the mushroom-shaped prominences common on many glaciers. Glacier tables frequently incline southward in north temperate latitudes, owing to the greater melting of their sup-

[1] "An Expedition to Mount St. Elias, Alaska," National Geographic Magazine (Washington, D. C.), vol. 3, pp. 127, 128.

porting columns on the south side. Eventually, the upraised block slips off its pedestal in a southerly direction, leaving a stump of ice to mark its site. When this happens, the process is renewed and the block again left in relief by the melting of the surrounding surface. The boulders and stones carried on the surface of glaciers thus receive many falls, and become broken and more or less comminuted. This illustrates the fact that not all of the crushing and commingling of rocks performed by a glacier takes place deep within or beneath its mass.

Moraines on the surfaces of glaciers are composed in a great measure of blocks of stone, which protect the ice beneath, as stated above, and produce still more marked inequalities of the surface. What appear to be massive embankments of stones and dirt are many times ridges of ice covered with a veneer of débris only a foot or two thick. The slow melting of the ice beneath superficial moraines causes the larger and less angular stones to slide and roll down the sides of the ridges, thus leading to a rude assortment of the material, with reference to size and shape. Such an assorting may be seen in the side view of a medial moraine shown in Figure 8. The friction and impact of the frequently disturbed rocks cause breakage and the formation of angular gravel, and even clay. Disintegration and weathering are thus promoted, and the surface material becomes divided into smaller and smaller masses the farther it is carried or the longer it remains on the ice.

When there are several parallel moraines on a glacier the surface becomes exceedingly rugged; and when, in addition, crevasses cross such a region, it is frequently rendered entirely impassable. I well remember a long, weary march across the Malaspina glacier, when our route lay at right angles to fully a score of huge moraines, each one forming a ridge from 50 to 200 feet broad at the top, and rising 100 or 150 feet above the adjacent troughs. These ridges were completely sheathed with stones held in sockets of ice, which would frequently slip from beneath our feet and roll to the bottom of the escarpment. The sides of these ridges were so steep that we could ascend them only by choosing zigzag courses. Many were the slips and tumbles experienced during the day. Between the ridges that caused so much delay and fatigue, there were lanes from a hundred to several hundred yards broad, floored with comparatively smooth ice, which had been deepened by the melting of the glacier, where unprotected. When standing on the crests of the dark, stone-covered ridges one could trace their courses for miles on either hand, until a change in the slope of the glacier carried them

out of view. At right angles to their trend there was nothing in sight except the distant mountains and the seemingly endless expanse of barren and exceedingly desolate débris.

Masses of sand and gravel resting on ice behave in much the same manner as do rock masses and moraines, except that where they are left upraised above the wasting surface the grains and pebbles roll and slide downward, and the pedestal is transformed into a cone of ice sheathed with a thin covering of loose material. At times, many acres far out on a glacier, are studded with groups of these peculiarly regular cones or pyramids, from a few inches to ten or twelve feet in height. Not infrequently they bear a striking resemblance to Indian tepees; in fact, one might easily mistake a group of these structures for an Indian encampment.

Still greater inequalities occur when moraines rest on stagnant ice and basins holding lakelets are formed. The sides of these depressions melt, and the stones and dirt previously spread out as a general morainal covering over the surface fall into them. The surface material thus becomes locally concentrated. As melting progresses, the lakes are drained. These thick accumulations of débris protect the ice beneath and become elevated in the same manner as the sand cones described above; but the mass of the material being greater, and frequently containing large boulders, the cones formed are of large size, and in many instances have an elevation of 50 to 150 feet. Although looking like pyramids of rudely piled boulders, one finds on climbing their sides that they are really pyramids of ice with a comparatively thin sheathing of stones and dirt. Large boulders, perched on the summits of these rugged pyramids, become detached from time to time, and descend in small avalanches to the depressions below, illustrating, again, the process of breaking and disintegration which takes place in the débris covering the surfaces of glaciers.

While large rocks or thick masses of dirt and stones resting on ice protect it from melting, the reverse is the case with pebbles and other small objects, particularly those of a dark color, which become warmed through by the sun's heat during a single day, and lead to the melting of the ice beneath. Such bodies sink into the ice and are commonly found at the bottoms of little water-filled wells five or six inches deep. On glaciers, where there is a scanty covering of pebbles, each individual stone will be found at the bottom of a water-filled depression. Sometimes the holes are so abundant that in walking over the surface one really treads

on the summits of thickly set columns of ice, separating the depressions. Leaves are frequently blown far out on glaciers, and becoming warmed by the sun sink into the ice in the same manner as the pebbles already referred to, and even insects, especially butterflies, are conspicuous in such localities. On one occasion, when traversing an ice stream tributary to Malaspina glacier, I found a fish, about four inches long, at the bottom of one of these holes. The nearest water in which it could have lived was at least twenty miles away. The most probable supposition is that it had been carried to the place where found by a bird.

Melting and Drainage. — The silence on broad glaciers when the winds are still and the temperature below freezing is frequently oppressive. This is especially noticeable on summer nights, for after sunset even in summer the temperature falls below freezing on the surfaces of large glaciers; but when the morning sun warms the air, rills and rivulets are formed, and the murmuring of running water is heard on every hand. By midday, brooks and creeks, too deep and rapid to wade and too broad to vault over, are coursing along in channels of ice. But their existence is brief. Soon a crevasse is reached, and their floods pour down into the depths of the glacier with a deep roar, telling of caverns far below the surface. The crevasses into which surface streams find their way are frequently enlarged, and become well-like openings, or *moulins*, as they are termed, which are sometimes several yards in diameter, and of great depth. In many instances, these openings must penetrate to the very bottom of a glacier. When this happens, the boulders and stones that find their way into them are washed about, and are given a rotary motion by the descending waters, so as to act as veritable millstones, and grind the rocks beneath. The result of this action is the formation of pits and holes in the rocks, resembling kettles, and termed *pot holes*, in which the stones that made them may frequently be found. These peculiar excavations are well known in regions of former glaciation. Typical examples in the Glacier garden, near Lucerne, Switzerland, are familiar to many.

The surface melting of glaciers leads to the formation of broad, shallow lakes. These appear especially on the névés, and by the intensity of their deep blue color impart an additional charm to the wintry scenes reflected from their surfaces. The shores of such lakes afford favorable camping places for glacier explorers, since water, the only necessity of camp life to be found in such regions, can there be had without the

expense of time and fuel necessary to procure it by melting snow. Many times during two expeditions conducted by the writer on the broad névé fields of southern Alaska, we had occasion to pitch our tent by the shores of these snow-bound lakes, and fully appreciated the advantages they afforded. In other instances, when necessity required us to camp on greatly crevassed snow, our water supply was sometimes obtained from the crevasses by means of a bucket attached to a line.

The water formed on the surfaces of glaciers, and draining from the land surrounded by them, or lying in front and sloping towards them, finds its way into the ice and escapes by tunnels situated either at the bottom of the glacier or in the ice itself. At the ends of alpine glaciers, and about the margins of both piedmont and continental ice sheets, there are ice caverns from which flow turbid streams of ice-cold water. (Fig. B, Plate 17.) The archways are the mouths of tunnels into which one can sometimes penetrate for a long distance. The streams issuing from such openings are supplied by both surface and basal melting, and possibly also by subglacial springs. These tunnels appear in all stages of glacier growth, and are kept open even when ice sheets reach great dimensions. On Malaspina glaciers, the course of such tunnels can in some instances be followed for miles, by listening to the muffled roar of the rivers rushing along through ice caverns far below the surface. Some of the tunnels, through which the waters formed by the melting of glaciers escape, are known to be situated on the underlying rock, but in other instances the openings traverse the ice itself, perhaps several hundred feet above its bottom. The tunnels through the body of the ice are thought to have originated from crevasses which allowed the surface water to escape from one break to another, and maintain a continuous passage-way. But observations proving this to be the true explanation are wanting. In the sides of deep crevasses in the Malaspina glacier one sometimes discovers a circular opening several feet in diameter, which reveals the position of an abandoned tunnel. In traversing the extremely rough outer margin of the glacier referred to, these openings were at times of great assistance, as they allow an explorer to pass from one deep valley in the ice to another, and thus avoid a steep climb over moraine-covered ice.

The drainage of glaciers, particularly those of the piedmont and continental types, is of special geological interest, for the reason that vast quantities of mud, sand, gravel, etc., are carried into the tunnels through which the sub- and englacial streams flow, and either left on the bottoms of

the channels, or swept out at the margins of the ice and deposited in part over the adjacent land. The sediments now forming about the border of Malaspina glacier are of great volume, and of more geological interest than even the abandoned moraines left by the slowly retreating ice mass. As will be described, thousands of acres of dense forest are there being overwhelmed and buried by the deposits of streams, that pour out from the ice, heavily freighted with sediment and even sweeping along large boulders.

The chief characteristic of the streams that emerge from beneath glaciers is their peculiar turbidity or milkiness. In exploring regions where the glaciers are small and hidden in sheltered recesses about high peaks, one is frequently enabled to discover them by noting the character of the waters flowing from the mountains. Upland streams not fed by melting glaciers are usually clear and sparkling, except during storms, while those born in ice caverns are rendered opalescent, and have a peculiar greenish-yellow tint, on account of the extremely fine material suspended in them. This fine rock flour, as it is termed, is retained in suspension even after the streams emerge from the highlands and flow through adjacent plains. Deposits of fine sediment of peculiar geological interest are formed by such streams, and enable one to interpret similar accumulations termed *loess*, left about the margins of ice sheets that have now passed away, and along the stream channels leading from them. The bluffs of fine, yellowish, clay-like material along the Mississippi and Missouri are of this character.

What is a Glacier?

The preceding paragraphs contain, I believe, an enumeration of the principal characteristics of glaciers. Although it is difficult, and perhaps impossible, to frame a concise definition of a glacier which will embrace all ice bodies that should be properly included, and exclude other accumulations of snow and ice to which the name should not be applied, yet it seems safe to assert that any considerable mass of snow and ice which presents a number of the characteristics referred to above may with propriety be included in the term.

As a provisional definition, it may be said that a glacier is an ice body originating from the consolidation of snow in regions where secular accumulation exceeds melting and evaporation, *i.e.* above the snow line, and flowing to regions where waste exceeds supply, *i.e.* below the snow line. Accompanying these primary conditions are many secondary phenomena

dependent upon environment, such as the grain of the ice, crevasses, melting, laminations, dirt bands, moraines, glacier tables, ice pyramids, sand cones, etc., which may or may not be present. Glaciers, even of large size, may exist in which few and perhaps none of these details can be discovered. We may conceive of a glacier as flowing through a channel so even and so well adjusted to its progress that no crevasses will be formed. So little débris may reach its surface that moraines and all accompanying details will be absent. The most persistent features of an ice stream are, perhaps, the slow movement or downward flow in both the névé and ice regions, the stratification of the névé, and the laminated structure and grain of the glacier proper. Yet even these important characteristics may not be readily discernible, even in ice sheets that are unquestionably true glaciers. Although the brief definition given above may assist one in obtaining an idea of what constitutes a glacier, it is manifestly open to qualifications and exceptions. If we consider the snow line as defining the boundary between the névé and the glacier proper, it is evident that there must be numerous exceptions to the rule. As before remarked, during certain years, and at times for many years in succession, the snow line is much lower than at other times, and may even completely conceal the hard ice which usually protrudes below the névé. Again, an ice stream may end in the sea, and be broken off and float away as bergs, before the division into névé and glacier proper is distinguishable on the surface. One of the most characteristic features of glaciers is their slow flowing motion, yet in their old age this may cease, so that the limits between a true ice stream and an inert ice mass may be indefinite, and perhaps impossible to define.

From what has been learned concerning glaciers it is evident that they form one of the transition phases in the history of drainage in many regions, and that the variations they present, like genera and species in the organic kingdom, cannot be limited by hard and fast lines, but should be classified by means of comparisons with typical examples. From snow, hail, and frozen mists, usually on elevated regions, the granular ice-snow of a névé is formed. By pressure and alternate softening and refreezing the névé is changed into compact glacial ice, but the plane of separation is indefinite, and no one can say where in a vertical section, the névé ends and the true glacial ice begins. Both the névé and the glacier proper are wasted by melting when the temperature is above 32° of the Fahrenheit scale, and the solid drainage is transformed to a liquid condition.

Glacial Abrasion.

Worn and Striated Rock Surfaces. — The movement of glacial ice causes friction and leads to the grinding, smoothing, and scratching of the rocks over which it passes. The intensity of this grinding can be appreciated to some extent by considering the force with which a thick ice mass presses on the rocks beneath. The weight of a cubic foot of ice is about fifty-seven pounds; hence a glacier 1000 feet thick, which is by no means the maximum, would exert a pressure on its bed of twenty-eight tons to the square foot. A movement of ice charged with sand and stones under such a pressure cannot fail to produce abrasion of the rocks beneath.

As will be shown in a future chapter devoted to theories of glacial motion, the precise mechanics of glacial flow is not clearly understood. It is well known, however, that the ice is not forced along as a rigid body. If such were the case, the grinding would be far more intense than is now believed to occur. It is, also, known that the flow of glacial ice is at least analogous to the flow of what are commonly considered plastic solids, as pitch, for example. In an ice stream the movement is most rapid at the surface at a distance from its borders, and decreases toward the bottom and sides, where the friction is greatest. Under similar conditions the movement of clear ice is greater than when it is charged with débris. The study of glaciers has shown, also, that sometimes the ice is sheared, and a forward movement is accomplished by a thrust of the upper portion of the mass over the lower portion. However accomplished, the fact remains that there is frequently a movement of even the sand-charged layers at the bottom, and that friction does occur between the ice and the underlying rock.

The conditions governing the flow of glaciers are so complicated that varying results are to be expected. When the bottom layer is heavily charged with débris, and, especially when containing a large proportion of gravel and stones, the friction is increased, and may possibly become so great that the bottom layer will be practically stagnant and allow the clearer ice above to flow over it; or a shearing of the mass may result, and the lower portion remain stationary for a time, while the upper portion moves on. Probably the most favorable conditions for rock abrasion are when the bottom of a glacier is lightly charged with sand, and the surface of contact with the rocks beneath is lubricated with water. That glaciers abrade the rocks over which they pass, as already

stated, there is abundant evidence. At the lower end, and along the sides of many alpine glaciers, the ice charged with sand and stones may be seen in direct contact with the smooth, polished, and striated rock surfaces. Below glaciers that have recently retreated, and where the surface is still bare of vegetation, records similar to those just mentioned may be observed in thousands of localities. The same is true, also, over vast regions that are known to have been formerly glaciated; while on adjacent areas, where the conditions are similar, excepting that they were not occupied by ice, the peculiar and not easily mistaken evidences of ice abrasion are lacking. We have, therefore, both positive and negative evidence pointing to the conclusion that glaciers abrade the rocks over which they flow.

Smoothed and Striated Rock Surfaces not Produced by Glaciers. — There are markings that simulate glacial polishing and striation, and might be mistaken for them, but are produced by other agencies. River ice, especially when swept along by freshets, sometimes scratches and striates the rocky ledges with which it comes in contact, but this action is confined within narrow vertical limits, and the marks produced are by no means so regular, or so deeply engraved, as those frequently made by glaciers. The abrasion of river ice was observed by the writer under favorable conditions along the Yukon river, but it did not appear as if the smoothing and striation produced in that way, except, perhaps, when only limited exposures were observable, could be easily mistaken for the work of glaciers.

The action of floe ice on the shores of lakes and northern oceans, when driven landward by wind pressure, on shelving beaches, makes the nearest approach to glacial abrasion and striation that is known. Except that the action of floe ice is confined to narrow vertical limits, it is difficult to understand how the planing and striation it produces on the rocks beneath could, in the absence of other data, be distinguished from the work of glaciers. Glaciers smooth and striate vertical walls, as well as flat surfaces, however, and make these and other records at all elevations from the surface of the sea — and to a limited extent even below sea level — up to the summits of lofty mountains. It is to be expected, also, that the records of floe ice would be accompanied by other evidence, such as deposits of clay and sand containing marine or lacustral shells, and topographic features due to the abrasion and deposition produced by waves and currents. When a considerable body of evidence is in hand in connec-

tion with the abrasion of rock surfaces in a given locality, there usually remains no room for doubting in what way the planing and striation were produced.

Special Features of Glaciated Surfaces. — The minor changes produced on rock surfaces by the movement of ice over them are so numerous that attention can only be directed at this time to those that are most common and most characteristic. The details of these wonderful inscriptions can only be appreciated by studying the originals.

Rock surfaces that have been subjected to the grinding of an ice sheet, or crossed by even a small alpine glacier, are frequently found to be worn and the angles and prominences rounded and planed away. All weathered and oxidized portions of the preglacial surface are removed, and the fresh hard rock exhibits a polish approaching that given by marble-workers to finished monuments. The hardest and finest-grained rocks receive the most brilliant polish. Limestone, granite, and quartzite, especially, are frequently so highly burnished that they glitter in the sunlight with dazzling brilliancy. On such surfaces there are usually scratches and grooves, frequently in long, parallel lines, which show the direction in which the ice moved over them. These markings vary in size from delicate, hair-like lines, such as might be made by a crystal point, to heavy grooves and gouges, a foot and sometimes several feet deep, which frequently run in one general direction for many yards and even several rods, and indicate by their straightness and evenness that the engine which made them was one of great power and moved steadily in a continuous direction. In regions formerly occupied by continental glaciers, particularly, two, and possibly three, well-defined series of parallel striations are sometimes observable on the same surface, crossing each other at varying angles. The most probable explanation of these double or triple inscriptions is that the direction of the ice current varied with the growth and decline of the glacier which made them, or that the ice flowed in great swirls or eddies, as in the case of the Malaspina glacier, and that the direction of these currents changed with variations in the volume of the glacier, or perhaps with variations in the amount of débris in the ice. On small areas the parallel striations appear straight, but if one could examine square miles of surface it would probably be found that the lines are frequently portions of broad curves.

Occasionally the more strongly marked glacial grooves in resistant rocks, like hard limestone and quartzite, exhibit curved or semilunar cracks, which cross the furrows from side to side at quite uniform intervals of a fraction of an inch up to an inch or more, and are convex in the direction of the former ice movement. These "chatter marks" are thought to have been formed by pebbles that were checked in their movement by friction, and when the force became sufficient to carry them onward, were forced forward suddenly, perhaps turning over, and struck the rock with such force as to produce cracks. A similar action may be observed in sliding bodies, as when the wheels of a car slide on the track and a jar is felt when they slip and are arrested. These peculiar semilunar cracks are not confined to bottoms of grooves, however, but appear on flat surfaces, where they are sometimes two or three inches or more in length, and are separated by intervals fully as great. These larger cracks, or "disrupted gouges," as Chamberlin has called them, are concave toward the point of the compass from which the ice came.

Another characteristic feature of glaciated surfaces is observed when hard knobs occur in rock, as, for example, when limestone is charged with small masses of chert, or with silicified shells and corals. In such instances the hard portions are left in relief by the abrasion of the softer matrix. Starting from each elevation there are frequently raised ridges, tapering to a point in the direction of the ice movement, and showing the manner in which the soft rock in the lee of the prominences was protected. On the opposite side of such knobs, *i.e.* on the side from which the ice came, the rock is sometimes worn into a furrow, which bends around the obstruction, and from its form indicates that the ice behaved as a plastic body and moulded itself to the surface over which it flowed.

Many other features of ice-worn surfaces might be enumerated, but in an elementary introduction it is perhaps better not to burden the reader with details.[1]

[1] In the report on "The Rock Scorings of the Great Ice Invasion," by T. C. Chamberlin, in the 7th Annual Report, U.S. Geological Survey, the reader will find many illustrations of ice abrasion, accompanied by clear and concise explanations of the manner of their formation, which will enable him to interpret such inscriptions for himself wherever found.

Glacial Deposits.

The morainal material carried by glaciers either on their surfaces or within their mass, is left when they melt, and forms accumulations to which, in part, the term *moraine* is still applied. The characteristics of such abandoned moraines are frequently well exhibited in mountain valleys from which glaciers have recently retreated. The most common of these deposits are briefly described below.

Lateral Moraines. — The débris accumulated on the borders of an ice stream, and constituting the lateral moraines of a living glacier, is left when the ice melts and appears as a ridge or terrace at varying elevations. Steep-sided mountain valleys are frequently bordered on either side by ridges of this character, which may be situated 1000 feet or more above the bottom of the trough and clearly traceable for miles. On the precipitous sides of such valleys, above the highest of the abandoned moraines, the slopes are usually rough and irregular, and bear evidence of the work of streams and rills descending from higher elevations, as well as other results of atmospheric waste; while below the horizon referred to the relief is subdued, and the valley has the smooth and flowing contours characteristic of ice work. Moraines of this character are frequently similar to stream terraces, but usually have a raised outer margin, and besides are composed of angular and unassorted material.

Terminal Moraines. — At various stages in the retreat of an ice stream, the lateral moraines on its sides are united by a terminal moraine, which crosses the abandoned bed of the glacier and forms a somewhat regular and usually crescent-shaped pile of stones, gravel, and sand, which is convex down stream and in many instances 100 feet or more in thickness. Between successive terminal moraines the bottom of the trough may be deeply filled with morainal material, deposited without special arrangement, and in many instances evidently accumulated beneath the ice as a "ground moraine." These low spaces between well-defined terminal moraines are frequently occupied by lakes or by grassy meadows, and furnish some of the most charming features of mountain scenery.

Morainal Embankments. — When a glacier is prolonged beyond the entrance of a mountain valley and reaches an adjacent plain, it

may expand and end in a semicircular ice foot, or preserve its stream-like form and finally melt without expanding laterally. The marked contrast in the behavior of different glaciers in this respect depends on the relative abundance of débris in their lateral and in their terminal moraines. When the débris on the margins of a glacier is small in volume, the ice has freedom to expand on getting free from the valley through which it descended, but when the margins of the prolonged stream are more heavily charged with débris than its extremity, lateral expansion is checked, while the clear ice at the extremity flows on. The ice advances between the stagnant borders of the stream to a greater or less distance, depending upon the supply from the higher mountains; and when it retreats, the heavy lateral moraines are left as parallel ridges with steep slopes on each side. These ridges frequently resemble great railroad embankments. The best examples of structures of this character that have been described are situated at the east base of the Sierra Nevada, in Mono valley, California.[1] Their general appearance is shown in Plate 4.

Morainal embankments, like lateral moraines on the sides of a valley, may be united by terminal moraines so as to form lake basins. When the terminal moraines are composed of coarse material and are too open to retain water, or when they have been breached by overflowing streams, grassy meadows and forest-covered parks, frequently of great beauty, occupy the spaces between them which were formerly filled by the retreating ice stream.

Frontal Moraines. — Moraines left by piedmont and continental glaciers are of the same general character as those deposited by alpine glaciers, but are frequently of vast extent. The frontal moraines of continental glaciers corresponding to the terminal moraines of local ice streams, are in some instances a score or more of miles broad and not only hundreds but thousands of miles long. Where two lobes of a continental glacier come together their frontal moraines are united and form what is known as an *interlobate moraine.* The best known examples are in the upper Mississippi valley, and mark the junction of the larger marginal extensions, or lobes, of the Pleistocene ice sheet of that region.

[1] "Quaternary History of Mono Valley, California," 8th Annual Report, U. S. Geological Survey, pp. 360–368, Pls. 35, 36.

Till. — Besides the irregular piles and ridges of unassorted débris composing the moraines formed about the margins of glaciers, there are accumulations of clay, filled at times with stones and boulders, which are deposited beneath the ice during its advance, and form what are frequently termed *ground moraines*. This material is widely spread over formerly glaciated regions, and is now generally designated by the Scottish name *till*, and is less frequently spoken of as *boulder clay*. The term *boulder clay*, however, has been given a somewhat different meaning by a few authors.

The characteristics of till are its compactness, due to the pressure to which it was subjected beneath the ice, and the worn and striated condition of many of the pebbles and boulders scattered irregularly through it. As till was not exposed to the atmosphere during its deposition, and, on account of its compactness, is impervious to surface waters, the material of which it is composed is in an unweathered condition and frequently of a bluish color, owing to the fact that the iron contained in it has not been oxidized. Its unweathered condition is in marked contrast to the surface moraines of many glaciers and to ancient glacial deposits which have been long exposed to the atmosphere.

Drumlins. — The abandoned paths of great glaciers are sometimes marked by smooth, oval hills that are lenticular in horizontal sections and have their longer axes parallel to the movement of the ice which formerly covered them. These peculiar and easily recognized eminences are, in the case of certain typical examples, about 500 feet in least diameter, with a length of from 1500 to 2000 feet, and a maximum height of from 50 to 150 feet. They exhibit many variations in size and shape, however, some being nearly circular, *mammillary hills*, and others *lenticular hills*, in which the longer axis is two or three times as great as the shorter axis. In some instances they form narrow ridges several miles in length. The beautiful curves formed by their crests when seen from the side, is illustrated by the outline of a typical example near Groton, Mass., here presented. They occur at all elevations from sea level, and even below that horizon, to 1500 feet or more above tide, and are found on uneven, rocky ground as well as on smooth plains. They are composed of compact till which is frequently laminated, and seldom exhibit evidences of stratification or other water action. Boulders and large angular stones occur within their mass, and scattered over their surfaces. These peculiar hills, for which the Irish

term *drumlin* is now generally adopted, have been studied especially near Boston, and occur also in many other parts of New England. They are abundant in the upper portion of the Hudson River valley, in central New York, and have been reported from Michigan and Wisconsin. In general they are situated well within the terminal moraine which marks the southern limit of the last ice invasion of northeastern North America. Many drumlins in the Connecticut and Hudson val-

FIG. 2. — DRUMLIN NEAR GROTON, MASS. AFTER FRYE.

leys, and other similar regions, are partially or wholly buried beneath Champlain clays, which were deposited during a time of land depression immediately after the last recession of the ice. Thus far, drumlins have not been observed in connection with existing glaciers. This is due, perhaps, to the fact that they are not known to originate beneath glaciers of the alpine type, and also because they seem to be a phase of the behavior of the somewhat central portions of large ice sheets, and are only open to view when the ice has withdrawn.

The characteristic *whaleback* shape of drumlins, the compactness and frequent lamination of the till composing them, as well as other facts in connection with their composition and distribution, have led to the generally adopted conclusion that they were formed beneath moving ice sheets. Various hypotheses have been proposed to explain their origin, but thus far opinion is divided in reference to the precise manner of their formation.[1]

Without attempting to present a review of the various hypotheses that have been advanced in reference to the origin of drumlins, I venture to suggest that the effect of débris on the flow of ice enclosing it may furnish the desired explanation.

The presence of débris, *i.e.* boulders, stones, sand, dirt, etc., in glacial ice, increases its resistance to motion, as will be more fully discussed in

[1] A discussion of the origin of drumlins, by Warren Upham, containing references to previous papers on the same subject, may be found in the Proceedings of the Boston Society of Natural History, vol. 26, 1892, pp. 2-17.

advance. Débris included in ice may be said to stiffen it and to decrease its plasticity; or, in other words, increase its resistance to forces tending to shear it. With this principle in mind, we are led to conclude that if a mass of débris is included in a glacier, motion in the débris-charged mass will be retarded, and the adjacent clear ice will flow around it. When the débris reaches a certain proportion, varying with conditions, motion will cease, and if the rate of flow of the clear ice does not increase, the débris-charged mass will remain stagnant. If the débris is most abundant about a central nucleus, and becomes less and less abundant in all directions from the nucleus, the flow of the ice will be least in the center, or if the débris is there sufficiently abundant, will remain stagnant, while motion in adjacent portions will increase in a definite ratio until the normal flow of clear ice under given conditions is reached. If a nucleus of débris, as above postulated, is situated in the central part of a glacier, with clear ice beneath, it may behave like a boulder and be carried bodily forward; but if situated at the bottom it will retain its position, and the clear ice will flow over it. If the ice flowing past the stagnant mass has earth and stones scattered through it, the débris reaching the nucleus will be retarded and the clear ice flow on. The nucleus of débris would thus receive additions and be compacted and moulded by the clear ice, or ice but moderately charged with foreign matter, flowing past it. A shape presenting least resistance to the flowing ice would thus be acquired, and the longer axis of the stagnant mass would be parallel with the direction of glacial flow. Under this conception of the growth of drumlins, the fact that they frequently, and possibly normally, contain débris that has been derived from lower levels presents no difficulty, since ice under pressure behaves as a viscous fluid, and will flow in the direction of least resistance. If the resistance at the sides of a stagnant nucleus was greater than over its summit, the approaching ice would rise and flow over the obstruction, carrying with it the débris contained within its mass. The varying forms of drumlins, the fact that they sometimes cover a nucleus of rock-in-place, their laminated structure, remarkable compactness, and general flowing outlines, all seem to harmonize with the view of their origin here suggested.

Certain drumlins of what may be termed the New York type, *i.e.* those that are greatly elongated, are not symmetric, but their ends in the direction from which the ice came which moulded them into shape are moderately broader and more blunt than the opposite extremities. These elongated hills may be said to have the shape of half a cigar cut lengthwise,

the larger end of the cigar pointing in the direction from which the ice came, which formerly covered the region where they occur. The sides of these hills, as is common with all elliptical or elongated drumlins, are more precipitous than the terminal slopes. On the larger or proximal ends, of several cigar-shaped drumlins observed by the writer in Washington county, New York, there is a noticeable increase in the number of boulders scattered over the surface, while at their tapering or distal extremities, fine débris greatly predominates, and is noticeable beyond, where the slope of the hills is lost. In these examples, coarse débris seems to have been deposited on the enlarged proximal ends, while the sides and distal portion suffered erosion, which removed the larger stones.

Under the hypothesis here proposed, drumlins are considered to have grown by the accumulation of débris about a central nucleus either of solid rock or of ice charged with stones to such a degree as to increase its resistance above the shearing forces brought to bear upon it; the added material being derived from the ice which flowed past it. The location of a drumlin would be determined by the presence of débris sufficiently abundant to cause stagnation in the ice containing it, which would vary with the rate at which the ice moved. When the ice contained but little débris it might all be carried forward; when the débris was in excess, it might be left in a general sheet, without special form. The most favorable conditions would be when certain threads, so to speak, of the ice current were lightly charged with débris, which on account of changes in the contour of the land over which the ice flowed, or variations in velocity due to other causes, would become sufficiently abundant at certain localities to check the flow of the débris-charged ice and cause it to become stagnant. The ice current would then add fresh débris to the stagnant nucleus, and a drumlin representing the excess of deposition over erosion would result.

The hypothesis outlined above has not been subjected to severe tests, and is introduced here in the hope that it will stimulate the student to make observations in the field, which will either sustain it or lead to its modification or rejection. In the study of the origin of topographic forms, many trial hypotheses have to be introduced and their value tested, in order to arrive at a true explanation. The above may be considered an example of such a *working hypothesis*. It is the duty of the compiler to take his reader as far as present knowledge seems to warrant, and to point the way into the unexplored country beyond.

I trust this little excursion beyond generally accepted conclusions will encourage the student to continue the investigation.

Glacial Sediments.

Deposits made by streams while yet confined by glacial ice, and for some distance after escaping from its borders, may for convenience be termed *glacial sediments*, in distinction from *glacial deposits* made directly from the ice and classified as moraines, till, drumlins, etc. These fluvio-glacial sediments are characterized by the worn and rounded condition of the sand, pebbles, and boulders composing them, and also by their more or less perfect stratification; while glacial deposits are, in the majority of instances, composed of unassorted, angular débris. Glacial sediments are in reality stream deposits made under peculiar conditions, determined by the presence of land ice. For this reason, they are of greatest interest when studied in connection with other glacial phenomena. The deposits here referred to are designated in many geological books, some of them of recent date, as modified drift; the early supposition on which this term is based being that they consist of glacial deposits that have been worked over and modified by streams. The leading characteristics of some of the best-defined deposits made by glacial streams are briefly described below.

Osars. — In formerly glaciated regions there are, in certain instances, long, gently curving, and sometimes tortuous ridges, trending with the direction of former ice movement, and composed of water-worn sand and gravel. When their internal structure is exposed, they exhibit more or less well-defined cross-bedding or oblique stratification, produced by rapid water currents; and on their surfaces large, angular boulders are frequently to be observed. Ridges of this character, sometimes 50 to 150 feet or more in height, and perhaps scores of miles in length, have been named *osars*, and are believed to have been formed by streams flowing in channels beneath ice sheets. The large, angular stones resting on them are of the same origin as the similar boulders on the surface of drumlins already referred to, and were deposited when the ice in which the osars were formed was melted.

Kames. — Other accumulations of water-worn sand and gravel, deposited beneath glaciers or about their immediate margins, have irregular shapes and form hills and knolls with undrained basins between. These

peculiar and frequently very picturesque topographic forms are known as *kames*. They are believed to owe their origin to the drainage of glaciers, and to have been formed by the deposition of gravel and sand in cavities beneath the ice, or after being swept out from ice sheets by the streams flowing from them and dropped in open channels in their margins. These are the most common of topographic forms composed of glacial sediments, and, like osars, frequently have large, angular blocks of rock scattered over their surfaces, and are sometimes completely coated with what was at one time englacial or superglacial material. They differ from osars in the fact that they form irregular hills with basins between, instead of long, winding ridges; and are distinguished from drumlins, since they are composed of water-worn sand and gravel, instead of till, and differ in their outlines. Their distinguishing characteristics are, especially, the irregularity and frequent changes in the character of the layers of which they are composed, their knob and basin topography, and the fact that in general they trend at right angles to the direction of movement in the ice sheet to which they owe their origin.

Sand and Gravel Plains. — About the margins of regions formerly covered by ice sheets and associated with osars and kames, there are frequently broad plains composed of irregularly stratified sand and gravel. These are the deposits made by overloaded glacial streams on emerging from restricted channels in the ice and expanding and dividing into many branches, and consequently dropping a large part of their loads, or flowing into lakes where their sediments were deposited.

The formation of sand and gravel plains, both by subdividing streams and in bodies of still water, may now be seen in progress about many glaciers. Conspicuous examples occur at the extremities and along the borders of several glaciers in Alaska. About Norris glacier in Taku inlet, shown in Plate 11, there are large deposits of sand, forming a low, gently sloping plain, across which the feeding stream divides into many distributaries. Other deposits of this same general character will be mentioned in advance in describing the Malaspina ice sheet.

Abundant examples of the deposits referred to above occur in the region occupied by morainal material in the northeastern part of North America, and also for many miles southward from the southern limit reached by the ice during what is generally termed the Second Glacial epoch. Plains of sand and gravel, either formed in small lakes and having horizontal surfaces, or laid down by bifurcating streams and having gently

sloping surfaces, make up a very large portion, and perhaps the major part, of glacial deposits over great areas in the region of the Laurentian lakes. At times these plains are marked by depressions, frequently rudely circular in outline, with steep banks of gravel and sand, and in such instances have acquired the name of *pitted plains.* The pits dotting their surfaces, and forming a marked characteristic of their topography, are believed to have been formed by the melting of isolated ice bodies which were surrounded or perhaps deeply buried by the gravel and sand during the last retreat of the glaciers.

CHANGES IN TOPOGRAPHY PRODUCED BY GLACIERS.

Glaciers have a twofold and opposite effect upon the relief of the regions they occupy. The abrasion produced by moving ice masses tends to reduce and smooth out inequalities, cut away prominences, and, as a minor feature, excavate rock basins. The deposits formed by glaciers, either directly or through the agency of streams, in many cases fill up and level off previously formed depressions, but in other instances, especially during retreat, tend to accent the relief of the surface and produce inequalities. The débris carried by ice streams and by ice sheets is left in confused heaps when melting takes place, and produces well characterized topographic forms. Frequently these deposits cover immense regions, and are striking in appearance, and vary abruptly in relief. The sediments of glaciers, and particularly the fine débris washed from them by outflowing water, fill inequalities, and on the whole, except in the case of osars and similar accumulations, tend to subdue and make uniform previous inequalities of the land.

About the margins of existing glaciers that are retreating, there are barren areas in which the topographic forms peculiar to glacial action are well displayed. In such instances one finds tumultuous piles of earth and stones, now rising into knolls and steep-sided hills, and, again, sinking into dales and sand plains with but little variation in the surface contours. One of the most striking features in these fresh morainal deposits is the presence of many depressions without surface outlets and very frequently containing lakes. The drainage is markedly immature.

On old moraine-covered areas the ruggedness is commonly concealed somewhat by vegetation, and many of the lakes that formerly existed in the depressions are transformed into bogs and grassy meadows. Streams originating in such areas cut channels for themselves and tend still

further to drain the land. As time goes on, a well-developed drainage system is established. The lakes disappear, and the work of the streams in reducing the country to base level, *i.e.* the level of standing water into which they discharge, is carried forward much the same as in regions that have not been affected by glacial action. This task is frequently greatly delayed, on account of the climatic conditions and for the reason, also, that glacial deposits, especially osars, kames, etc., composed of unconsolidated gravel and sand, are sufficiently porous to absorb the rain water that falls upon them and allow it to percolate slowly away, thus robbing it of its power to erode. The most prominent relief of glaciated lands is frequently such as is produced by open, porous deposits of the nature of kames and osars. These retain their primitive form, while mountains of indurated rock yield to the forces of the atmosphere and are sculptured in various ways.

The most pronounced topographic evidences of the former presence of an ice sheet are irregular moraines ; undrained basins; numerous lakes, long, winding gravel ridges, or osars ; tumultous hills of gravel, or kames ; lenticular hills of till with smooth surfaces, or drumlins ; broad and frequently gently sloping gravel plains, sometimes with pitted surfaces ; boulders, occasionally perched on hilltops and mountain sides ; faceted and striated stones ; outcrops with smooth and rounded contours, and polished and striated surfaces.

With this elementary discussion of the general characteristics of glaciers and of the records they leave when climatic changes lead to their disappearance, we will pass in the following chapters to an account of the glaciers now in existence in North America.

CHAPTER II.

GENERAL DISTRIBUTION OF THE GLACIERS OF NORTH AMERICA.

THE glaciers of North America are confined to the Cordilleran mountain series and to the Greenland region.

Cordilleran Region. — The Cordilleran series is, in fact, a family of mountain systems in most of which there are several independent ranges and multitudes of individual peaks. It is the longest mountain series in the world, extending as it does from Cape Horn to the western extremity of the Aleutian islands, a distance of over 7000 miles. In Central America it is represented by a single system, in Mexico it becomes divided, and in the United States it is definitely separated into the Rocky mountains, Sierra Nevada-Cascade, and Coast systems. In Canada the breadth of the series increases northward, and four well-defined mountain systems are recognized, viz.: the Rocky, Gold, Coast, and Vancouver. What is known as the Coast range in Canada is not a continuation of the Cascade mountains, as sometimes stated, but is distinct from them both topographically and geologically. *Vancouver system* may sound strange to many readers, but is an appropriate designation, proposed by the Geological Survey of Canada, for the great system of uplifts beginning at the south in the Olympic mountains, Washington, and extending northward through Vancouver and Queen Charlotte islands, and attaining its greatest development on the coast in southern Alaska, and finally terminating at the west in the Aleutian islands.[1]

In Canada and Alaska the mountains of the Cordilleran series near the coast become more elevated than those of the interior and bend abruptly westward in the central part of their course. The eastern system in the same series is prolonged northward, and judging from the meagre information at hand, decreases in height and ends indefinitely before reaching the shores of the Arctic ocean.

[1] A. R. C. Selwyn and G. M. Dawson, "Descriptive Sketch, Geological and Geographic, of the Dominion of Canada," Montreal, 1884, p. 35.

Several of the great volcanic peaks of Mexico, which belong with the Cordilleran series but are of secondary origin, attain an elevation of from 17,000 to over 18,000 feet, and reach the horizon of perpetual snow. In some instances true glaciers of small size are said to exist about their summits, but little if any reliable information is available concerning them, however, and we are obliged to pass them by.

The southern limit of glaciers in the United States is in the High Sierra, California, in about latitude 39°. The ice bodies of that region are small, but have many of the essential features of the most typical ice streams of the alpine type. They are confined to sheltered amphitheatres about the highest peaks, and do not extend lower than about 13,000 or 12,000 feet above the sea. In most instances they are at the northern base of sheltering precipices, and terminate before reaching the upper limit of timber growth.

In northern California, and in Oregon and Washington, glaciers are more numerous, of greater extent, and reach lower limits than in the Sierra Nevada, but are still confined to the higher portions of the more elevated peaks and do not extend to a lower horizon than about 6000 feet above the sea. In many instances they reach the upper limit of forest growth. The best examples cluster about the summits of Mount Shasta, Mount Rainier (Tacoma), Mount Baker, and other volcanic peaks of the same region.

In the Rocky mountains, glaciers are foreshadowed at the south by small snow bodies in Colorado, which certain travelers who have examined them consider worthy of being numbered among glaciers.[1] Perennial snow banks increase in number and in extent towards the north, and true glaciers occur in Montana and adjacent portions of Canada.

Glaciers are numerous in the Cordilleran series in Canada and furnish some of the most attractive features in the scenery of that wild and picturesque land, but unfortunately only meagre information concerning them is yet available. The best known examples appear in the Selkirk mountains, one of the loftiest ranges in the Gold system, and in the Coast mountains in the vicinity of the Stikine river. Further north, in the same great mountain series, bodies of perennial ice become more and more numerous, at the same time increasing in size, and reach their

[1] F. H. Chapin, "The First Ascent of a Glacier in Colorado," Appalachia, vol. 5, 1887, pp. 1–12.

An account of the occurrence of typical glaciers near McDonald lake, in northern Montana, by L. W. Chaney, Jr., was published in Science, vol. 2, 1895, pp. 792–796.

most magnificent development in southern Alaska. The most thoroughly ice-covered region in the Cordilleran series is in the vicinity of Mounts Fairweather, Logan, and St. Elias, and lies partially in Alaska and partially in Canada. Westward from that stronghold of perennial ice, as previously stated, the mountains decrease in elevation. The effect of this change, and probably also of accompanying variations in climatic conditions, is seen in the glaciers, which become smaller and more widely separated and are confined to higher and higher regions when traced westward to the Alaska peninsula and the Aleutian islands.

As one follows the great Cordilleran glacial belt northward from its first appearance in the High Sierra, the lower limit of perennial snow, or the "snow line," at first about 12,000 feet above the sea, descends lower and lower, until finally in the vicinity of Mount St. Elias it has an elevation of only 2000 or 2500 feet. Farther west, along the curve made by the mountains about the northern shore of the Pacific, the snow line again rises, and on the Aleutian islands has an elevation of perhaps 8000 or 10,000 feet. The glacial ice everywhere extends below the limit of perennial, névé snow, but is most thoroughly exposed in late summer or early autumn, when the true position of the snow line is sharply defined. In the High Sierra, the extension of glacial ice below the névés is but slight, and during seasons of unusual snowfall, or when the summers are exceptionally cool, may not be recognizable. Proceeding northward, the ice extension is more and more pronounced, until the region of maximum glaciation is reached. Thence westward the length of the tongues of ice below the snow fields decreases.

In the High Sierra, as already stated, the glaciers do not descend below about 12,000 feet; farther north they reach lower and lower limits, until in the vicinity of Stikine river, in about latitude 57°, they gain the sea level. Thence northward and westward to beyond Mount St. Elias, a distance along the coast of between 700 and 800 miles, there are hundreds and probably thousands of glaciers that descend practically to sea level, and scores that enter the sea and, breaking off, form bergs. Beyond the Mount St. Elias region their lower limit gradually rises.

At the southern end of the crescent-shaped belt of glaciers under consideration, the ice bodies are small and detached, and are separated from each other by intervening ridges and mountain peaks. Proceeding northward, they increase in area and in frequency, and unite one with another in the névé region. The snow belt broadens and finally becomes a confluent sheet 80 or 100 miles broad in southern Alaska, and narrows

again westward and is there broken into individual névés of limited extent similar to those of the High Sierra. The most thoroughly snow and ice-covered portion is in the region between Lynn canal and Cook's inlet, Alaska, where not less than 15,000 square miles of mountainous country is almost completely buried beneath a single vast névé field from which ice streams of the alpine type flow both north and south through rugged defiles in the flanks of the mountains. The southward flowing glaciers are larger, more numerous, and much longer than those that find their way northward, and, in gaining the low lands adjacent to the ocean, expand and unite one with another, so as to form broad plateaus of ice, known as piedmont glaciers.

Could the observer obtain a bird's-eye view of the western portion of North America, he would find that the Cordilleran glaciers form an irregular curve, broadest and reaching sea level in the Mount St. Elias region, and narrowing and becoming more and more elevated at both its southern and western extremities. The attenuated arms of this shining crescent are broken, for the reason that only the more elevated mountains near its extremities reach the horizon at which perennial snow exists. As in the crescent of light reflected from the surface of the moon, the mountains in the Cordilleran ice crescent where the belt is broadest are white to their bases, while only the peaks of the most lofty elevations at the extremities of the broken circle are brilliant. The length of this crescent of snow and ice is about 3000 miles. Its form is less regular, however, than the comparison made above might lead one to suppose, as its southern prolongation is broader and more broken than its central and western portions.

The study of the glaciers of the Cordilleras has only fairly begun, but it is hoped that what has already been accomplished will convince the reader that the subject is not only worthy of consideration, but of fascinating interest, and that the work of exploration should be continued.

Greenland Region. — In the eastern portion of North America glaciers are confined to Greenland, and to the islands adjacent to it on the west. The vast ice sheet covering nearly all of Greenland is of the continental type, and, as is well known, is the largest existing ice body in the northern hemisphere. Its extension northward has not been fully determined, but as nearly as can be judged it terminates in about latitude 82°. Its area is in the neighborhood of 600,000 square miles. If transferred bodily to the eastern portion of the United States, it would

extend from northern Maine to Georgia, and cover a belt of country 500 miles broad. Vast as this ice sheet is known to be, it takes what may be said to be second or third rank when contrasted with the continental glaciers that occupied Canada and a large portion of the United States in Pleistocene times. The exploration of existing glaciers derives one of its principal attractions from the fact that such studies assist in interpreting the records left by ancient glaciers in various parts of the world. This in turn brings one to the consideration of the still broader problems of the cause of climatic changes which favored the growth of vast Pleistocene glaciers in regions now enjoying a temperate climate, and inhabited by the most civilized people of the earth.

The glaciers on the islands to the west of Greenland are but imperfectly known, but from the somewhat meagre reports rendered by Arctic explorers, few of whom, it is to be regretted, have been trained observers in this direction, it appears that they are of the alpine type, although larger, and with broader névé fields in proportion to the extent of true glacial ice, than is found among the glaciers of Switzerland or other similar regions. A remarkable feature of the glaciers of the far north is that they frequently terminate in bold precipices of ice.

Having this general sketch of the distribution of glaciers in North America in mind, the reader will be enabled to locate in the outline plan the relations of the various ice bodies described in the following chapters.

CHAPTER III.

GLACIERS OF THE SIERRA NEVADA.[1]

THE Sierra Nevada, in many respects the most attractive mountain system in North America, attains its greatest elevation between latitude 36° and 38° 30′, or in a more general way, between Owen's lake and Lake Tahoe, California.

THE HIGH SIERRA.

To the more elevated portion of the Sierra Nevada the name "High Sierra" has been applied. Although the boundaries of the region thus designated are indefinite, it is well worthy of especial recognition, as it is a prominent and important topographic feature. Throughout its entire extent it bristles with rugged peaks, narrow crests, and inaccessible cliffs, overshadowing profound chasms, all of which combine to form one of the most rugged and picturesque mountain ranges in North America. The culminating point of this elevated region is near its southern limit, where Mount Whitney rises to an elevation of 14,522 feet above the sea, and is succeeded northward by Mount King, Mount Humphreys, and many other elevations scarcely less magnificent. Southward from Mount Whitney the Sierra declines rapidly, and the system is considered as terminating in that direction at Tehichipi pass, a little north of latitude 35°. Northward of Mount Whitney, there is a vast sea of rugged peaks and narrow mountain crests, separated by deep valleys, which render the region almost inaccessible to beings not equipped with wings. This is the High Sierra *par excellence*, as will be admitted by all who attempt to scale its giddy heights or thread its labyrinth of cañons. In the neighborhood of Mono lake a number of the more prominent peaks, of which Mount Lyell, Mount Ritter, Mount Dana, and Tower peaks are examples, exceed 13,000 feet in elevation. The range retains its rugged character all the way to Sonora pass, and even to Lake Tahoe, but northward of that "Gem of the Sierra" the mountains are less elevated.

[1] This account of the glaciers of the Sierra Nevada is taken almost entirely from a paper by the present writer, on the "Existing Glaciers of the United States," 5th Annual Report U. S. Geological Survey, 1883–84.

Very large portions of the High Sierra are composed of light-colored granite, but thinly clothed with vegetation, which imparts a monotonous gray tone to the rugged scenery. The peaks and crests overlooking Mono lake, however, have been sculptured from metamorphosed sedimentary rocks, and are frequently richly tinted. The landscape in this portion of the range is warm in tone, and presents pleasing and striking contrasts in comparison with the gray of the western slopes. Rugged and angular precipices rising to narrow crests, but softened in contour and varied in color on their lower slopes by lichens and alpine flowers, dark billowy forests of pine in the valleys, snow-filled amphitheatres, and hundreds of placid lakelets and rock-rimmed tarns are there grouped in pictures that are as delicate in detail and as pleasing in tone as they are majestic and far-reaching.

Besides the splendor of their scenery, the mountains to the southward of Mono lake present the additional attraction of living glaciers. These, although small, are well worthy the careful attention of every traveler.

Existing glaciers on Mount Dana and Mount Lyell were visited by Mr. G. K. Gilbert and myself during the summer of 1883. I also examined one at the head of Parker creek, a tributary of Mono lake. Others on Mounts Conness, McClure, and Ritter were explored by Mr. W. D. Johnson, my associate for several years in western explorations, while making a topographical survey of the region draining to Mono lake. Besides the glaciers actually traversed, a number of others were seen from commanding points, and their general nature almost as thoroughly determined as if their surfaces had actually been trodden. Our combined observations show that nine glaciers exist within the southern rim of the Mono lake drainage basin. A somewhat larger number are sheltered by the mountains, of which the dominant peaks are McClure, Lyell, and Ritter. It is in ice caves beneath these glaciers that the Tuolumne, Merced, and San Joaquin rivers have their birth.

The glaciers of the High Sierra are located between latitudes 36° 30′ and 38°, and at their lower extremities have an approximate elevation of 11,500 feet above the sea. The lowest seen is on the northern side of Mount Ritter, and terminates in a lakelet that is about 2000 feet below the mountain top, or about 11,000 feet above the sea. The glaciers observed are all small, the most extensive — that on the northern slope of Mount Lyell — being less than a mile in length, with a somewhat greater breadth. Nearly all occur in amphitheatres on the northern side

Mono Lake
See it

FIG. A. — MOUNT DANA GLACIER, CALIFORNIA.

On the northern side of the summit-peak of Mt. Dana.

FIG. B. — MOUNT LYELL GLACIER, CALIFORNIA.

The highest peak is the summit of Mt. Lyell.

of lofty peaks, where they are sheltered from the noonday sun by high cliffs and mountain ridges; and all flow northward, with the exception of a few cradled in deep *cirques* on the eastern side of the Minarets and Mount Ritter. So far as known, these are the most southern glaciers in the United States. Snow fields are reported by Mr. Johnson, however, as existing in the mountains to the south of Mount Ritter, at the head of some of the many branches of Owen's river. If these should prove to be veritable glaciers, they will extend the southern limits of the existing glaciers of this country a few miles farther southward.

MOUNT DANA GLACIER.

On the western shore of Mono lake the mountains rise abruptly from the water's edge to an elevation of 5000 to 6600 feet, and have been sculptured by storms and frosts into independent peaks of remarkable grandeur. As seen from Mono lake, the most conspicuous point along the serrate mountain crest outlined against the western sky is Mount Dana, which rises 6600 feet above the lake, and has an elevation of 12,992 feet above the sea. Although of grand proportions, this peak is but one among many prominent points crowning the divide between the drainage of Mono lake and the Pacific. From the southward, Mount Dana presents a somewhat rounded contour and is easy of ascent, but on the north its culminating cliffs form a nearly perpendicular precipice more than a thousand feet high. This northern face descends into a deep, narrow gorge leading northward, known as Glacier cañon. During the glacial epoch the whole extent of this cañon was occupied by ice, and formed a tributary to a still larger glacier flowing into Mono valley.

At the head of Glacier cañon, and surrounded on nearly all sides by towering precipices, lies the small ice body represented on Fig. A, Plate 2, to which the name Mount Dana glacier has been given. The picture shows nearly the entire extent of the glacier, and is from a photograph taken on an abandoned terminal moraine now retaining a lake of opalescent water, into which the drainage from the ice discharges. In the illustration the terminal moraine now forming about the border of the ice can be seen, as well as the crevasses, dirt bands, etc., that mark its surface. The glacier is about 2000 feet long in the direction of flow, but appears much foreshortened in the illustration. "Ice tongues" are seen extending upward from the névé. At the base of the largest of these peculiar ice tributaries a portion of a wide crevasse, or bergschrund, may be recognized.

This miniature glacier exhibits many of the essential features of greater ice streams, such as névé and glacier proper, crevasses, dirt bands, moraines, glacier tables, etc., as will be described in connection with similar features on neighboring ice bodies a few pages in advance.

Mount Lyell Glacier.

In traveling from Mount Dana to Mount Lyell, one finds it most convenient to pass down Dana creek, which flows southward from Mount Dana, to its confluence with Tuolumne river, and then ascend the deep, broad cañon of the latter stream. Tuolumne river has its birth at the extremity of the Mount Lyell glacier. It emerges from a cavern in the ice as an insignificant, dirt-laden brook. The snowy summit of Mount Lyell, as seen from the head of Tuolumne cañon, is shown in Plate 3. The majestic mountain, when viewed from this portion of the valley, is far more beautiful than any illustration in black and white can suggest. In the soft, gray light of morning, it has all the solemn grandeur of the Bernese Oberland. At sunset, when flushed with the rosy light of the afterglow, this shrine of the High Sierra rivals the splendor of Mount Rosa. To the right of Mount Lyell rises Mount McClure, which is scarcely less imposing than its companion; the former attains the height of 13,420 feet above the sea, and the latter is but 150 feet less in elevation.

The Tuolumne cañon, when followed still nearer its beginning, is found to lose its gentle grade and become rugged and precipitous. Its bed is crossed at intervals by irregular cliffs, that must have caused magnificent ice cascades in the great glacier that once flowed over them. The top of each steep ascent is usually separated from the base of the next higher one by a comparatively level tract, sometimes holding a grassy meadow or small, rock-enclosed tarn. This succession of cliffs and terraces forms a grand stairway, leading to the opening of the amphitheatre on the north side of Mount Lyell, where a magnificent panorama of the entire glacier may be obtained. The view given on Fig. B, Plate 2, is from near the outlet of the amphitheatre, and exhibits nearly the whole extent of the névé of the Mount Lyell glacier and of the small area of compact ice which projects from beneath it. In the panorama the terminal moraine of dirt and stones, now forming at the foot of the glacier, may be recognized, and also the rounded and worn rock masses that rise as islands in the central portion of the

glacier. Crevasses, contorted dirt bands, and moraines on the ice, although noticeable features when traversing its surface, are but indifferently shown in the illustration.

Parker Creek Glacier.

This glacier is situated at the head of a deep, high-grade cañon, down which Parker creek descends on its way to Mono lake. It is even smaller than the ice bodies on Mount Dana and Mount Lyell, but is yet a true glacier with a well-defined névé region, from beneath which descends a mass of ice that is crossed by dirt bands and crevasses, and has many minor features that duplicate the details of more extensive ice streams. About the lower margin of the ice there are comparatively large moraines forming concentric ridges, and indicating the rapid disintegration of the surrounding cliffs, since the material of which they are composed was derived entirely from that source. The mass of débris surrounding this glacier appears to exceed the volume of the ice of which it is formed. These moraines are more characteristic examples of the tumultuous débris piles formed by ice streams than any other deposits of the same nature now forming in the High Sierra. Like the majority of the glaciers of this region, the one at the head of Parker creek is sheltered by overshadowing walls, and flows northward. During the glacial epoch, the entire extent of the deep valley through which it flows was occupied by a glacier that descended upon Mono plain, and built huge morainal embankments more than a mile in length. These fine examples of the peculiar parallel embankments built by overloaded glaciers on emerging from mountain gorges are second in interest, however, to similar deposits at the mouth of the neighboring gorge, known as Bloody cañon,[1] and illustrated on Plate 4.

Characteristics of the Glaciers of the High Sierra.

That the ice bodies observed in the High Sierra, although small, are yet veritable glaciers, I trust will appear from the following somewhat detailed statement of observations:

[1] The instructive records left by Pleistocene glaciers in the neighborhood of Mono lake are described and illustrated in "Quaternary History of Mono Valley," in the 8th Annual Report of the U. S. Geological Survey, 1886-87, pp. 261-394.

Névés. — The distinction between névé and true glacial ice is plainly manifest on nearly all of the glaciers of the High Sierra. This is apparent not only when viewing them from a distance, but also while traversing their surfaces. In the case of the Parker Creek glacier, especially, the change from the granular snow of the névé to the compact ice of the glacier proper, can be discerned within the space of a very few feet. The névés, although usually dust-covered, are invariably white as compared with the rest of the glacier, and are composed of granular ice-snow. Their surfaces are almost entirely free from stones and dirt, and are rendered very rough and uneven by crests and spires of compact snow or névé ice, from two to five feet high, that result from the unequal melting of the surface. These "ice blades" have been described by Professor Le Conte, who refers their origin to the unequal melting of wind-rippled snow.

At their lower limits the névés pass into the glaciers proper, which in part they overlie, and acquire a ribboned or laminated structure, dirt bands, etc., characteristic of true glaciers.

Crevasses. — Marginal crevasses were observed in numerous instances, but they occurred in quite limited numbers in any individual glacier. In some examples, more especially in the névés, they are convex toward the head of the glacier, while others far down in the same series are straight, or have changed their curvature so as to be concave up stream. The crevasses are largest at the upper margin of the névés, and frequently correspond to the bergschrund of Swiss mountaineers. They vary from narrow cracks up to chasms six or eight feet wide, and frequently cross almost the entire breadth of the névé, thus rendering difficult the passage to the rocks above. The depth of the crevasses could seldom be determined, as the irregularities of their sides limited the view, but some were certainly not less than 100 feet deep. The crevasses were frequently partially concealed by arches of snow, hung within with vast numbers of icicles. The walls beneath these treacherous roofs are incrusted with large masses of well-formed ice crystals, with glittering faces half an inch in diameter, resembling the most beautiful transparent spar. The light in these fairy-like grottoes is of the most exquisite blue.

Lamination, or "Ribboned Structure." — This structure was seen in all the glaciers closely examined, but appeared most conspicuously near the lower extremity of the ice, where the layers are approximately horizontal. Hand specimens cut from the ice exhibited sections of alter-

MOUNT LYELL, CALIFORNIA, FROM TUOLUMNE VALLEY.

A nearer view of Mount Lyell Glacier is given in Fig. B, Plate 2.

nating narrow bands of compact blue ice and porous white ice, as plainly as could be desired.

Dirt Bands. — These were observed on nearly all of the glaciers, and were frequently marked, and even conspicuous, features of their surfaces. It required no peculiar condition of light and shade to make them discernible; on the contrary, they could be plainly distinguished at a distance of two or three miles. Viewed from a distance, they were seen to sweep entirely across the glacier in a series of graceful curves, concave toward the névé. Sometimes this symmetry was interrupted by irregular undulations, or even by contortions, as may be seen in the illustration of the Mount Lyell glacier. On Parker Creek glacier the dirt bands are about six inches broad over a considerable area, and occur at quite regular intervals of four to six feet, with comparatively clear ice between. In this instance, the dirt producing the bands was not confined to the surface, but could be seen to discolor the ice in well-defined strata, dipping into the glacier at a low angle with the surface. On all of the glaciers examined, the dirt bands were observed only below the lower limit of the névé.

In the study of the glaciers of Switzerland and Norway, particular attention has been given to the influence of ice cascades in producing lamination and dirt bands. In the Sierra Nevada glaciers, both of these characteristics are distinct and well marked, but ice cascades are absent. It seems evident, therefore, that the hypothesis which is apparently satisfactory in Europe does not agree so well with the phenomena observed in California.

In viewing many of the Sierra Nevada glaciers at a distance of a few miles, and approximately on the same level, it is apparent that their surfaces frequently have a slope of from 15 to more than 30 degrees, and are, in fact, sections of the ice bodies in which the internal structure is exposed. When seen in this manner the appearance of the glaciers is such as to lead one to suspect that the dirt bands are strata in the ice, or in reality "annual rings" formed by yearly accumulations of dirt on the névés. A similar explanation was long since advanced by Forbes after studying the dirt bands of apparently the same character on Swiss glaciers. Prof. H. W. Brewer has suggested a modification in this explanation to the effect that a year of exceptional melting — one of those years in which the névé is reduced to the minimum — would have the effect of combining the dirt accumulated during several years

into a single band, which would represent a climatic cycle rather than a single year. This explanation agrees best with the facts noted above.

Glacier Tables. — Blocks of stone perched on columns of ice, and usually designated *glacier tables*, did not form a marked feature on the ice bodies of the Sierra Nevada in 1883, except in one instance. On Parker Creek glacier they were numerous and in all stages of growth and decadence. Some of the blocks of stone were poised horizontally on pedestals of ice; others were inclined southward, or had been partially dislodged, and in some instances they had fallen and were lying on the southern side of pinnacles which had formerly supported them. Sketches of some of the more characteristic examples observed, drawn to a scale of about one foot to the inch, are here shown.

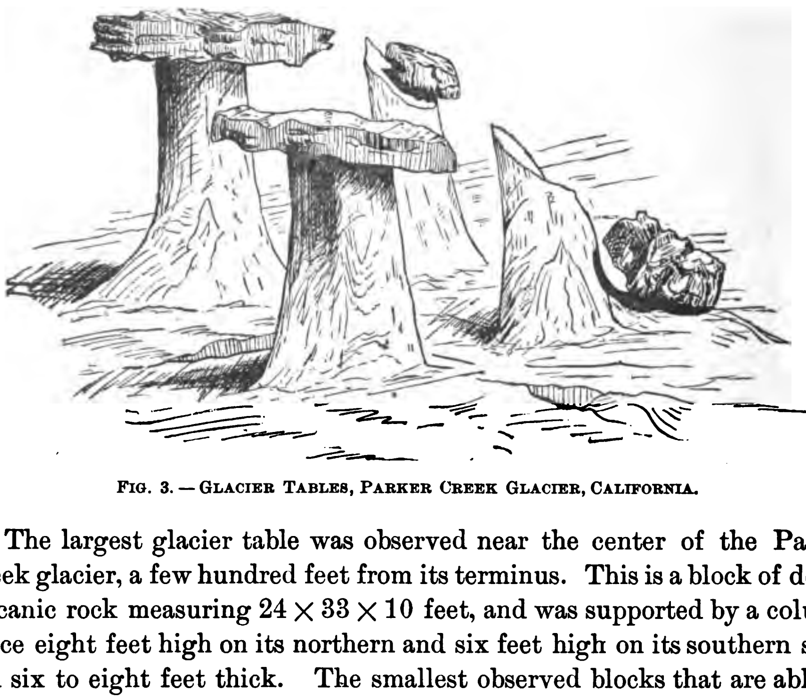


FIG. 3. — GLACIER TABLES, PARKER CREEK GLACIER, CALIFORNIA.

The largest glacier table was observed near the center of the Parker Creek glacier, a few hundred feet from its terminus. This is a block of dense volcanic rock measuring 24 × 33 × 10 feet, and was supported by a column of ice eight feet high on its northern and six feet high on its southern side, and six to eight feet thick. The smallest observed blocks that are able to protect the ice beneath sufficiently to form columns as the general surface melts away were found to be about 16 × 10 × 10 inches; when smaller than this they sink into the surface in a manner that is well known to all alpinists. Small pebbles are frequently seen at the bottom of little ice wells five or six inches deep, but good examples of sand cones and some of the other minor details of glacier surfaces were not observed.

Ice Pyramids. — As the forms included under this name furnish a detail of glacier surfaces not described before the glaciers of the High Sierra were examined, I shall transcribe my notes concerning them at some length.

On the lower portion of the Mount Lyell glacier, more especially than in any other observed instance, the surface bristles, over large areas in the névé region, with acute pyramids of snow-ice from a few inches to fully three feet in height, with bases having a diameter of perhaps one-half their height.

At the base of each pyramid on its northern side, there is invariably a stone, sometimes measuring five or six inches in diameter, or a number of loose pebbles, or a handful of dirt, which is usually depressed somewhat below the general surface of the névé. The side of the pyramid rising

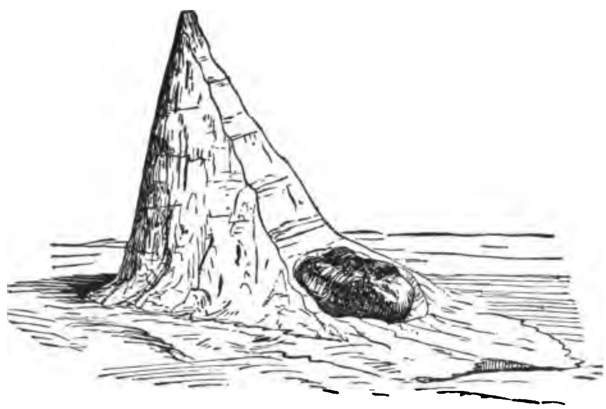


FIG. 4. — ICE PYRAMIDS, MOUNT LYELL GLACIER, CALIFORNIA.

above the stone, *i.e.* the northern face, is usually concave, in horizontal sections, and invariably composed of clear, compact ice, while the remainder of the structure is of the ordinary porous ice forming the glacier surface. Sometimes the nearly horizontal lamination of the glacier ice can be seen in the pyramids. A direct relation is noticeable, too, between the size and shape of the stones and the height and form of the ice pyramids rising above them.

In seeking an explanation of these phenomena, the only hypothesis that seems to satisfy the observed facts, assumes that a stone or mass of dirt lying on the surface of a glacier becomes heated and melts the porous ice beneath, and that the water thus formed freezes again into compact ice, which resists the sun's heat more thoroughly than the surrounding porous

ice, and hence is left as the general surface melts away. In nearly every instance, the stone at the base of the pyramid had been carried northward as it melted its way downward, thus forming the steep, northern slope of the pyramid, and at the same time tending to prevent the formation of a prominence on the northern side of the sunken block. The pyramids always point toward the noonday sun, hence the compact ice formed on the northern side of a pebble is more exposed than the ice on its southern side, and is, therefore, more rapidly melted.

Moraines. — No well-marked medial moraines were noticed on any of the Sierra Nevada glaciers. The reason for their absence is because the glaciers are simple ice streams, without tributaries. Lateral moraines resting on and inclosed in the ice at the margins of the glaciers were seen in many instances, and could be traced without difficulty to the cliffs from which they came. Terminal moraines, however, are common, and occur at the lower limit of every glacier observed, and owe their existence to the moderate amount of morainal material scattered over the surfaces or contained in the glaciers, without being concentrated into medial moraines. The terminals are remarkable for their size, when compared with the extent of the parent ice streams, indicating that the process now observed has been going on essentially as at present for a long term of years. The terminal moraine now forming at the lower extremity of Mount Dana glacier is approximately 1000 feet long by 30 or 40 feet broad, and apparently 100 feet or more deep. Below this, and partially united with it, is a second ridge of débris of somewhat greater dimensions, which is followed by other similar crescent-shaped piles lower down the gorge. The corresponding moraines at the extremity of Mount Lyell glacier are considerably larger, as are also the still more typical terminals at the foot of the Parker Creek glacier. In some instances these moraines were coated with loose rubbish and dirt that would be swept away by a single storm, indicating that they had received their last addition within a very few months.

The bottom of the Dana glacier was seen to be heavily charged with stones, pebbles, and sand, and to rest on a bed of boulders of a considerable thickness. This subglacial deposit may with propriety be termed a ground moraine.

Glaciated Surfaces and Scratched Stones. — The rock surfaces in the immediate neighborhood of the Sierra Nevada glaciers are frequently

polished and covered with grooves and scratches, but it is usually impossible to determine whether this is the work of existing ice streams, when somewhat more extended than at present, or whether it is a part of the vast glaciation imposed upon all the High Sierra during the glacial epoch. In some instances, however, there does not seem room for doubting that the markings were made during the past few years.

At the immediate foot of Mount Dana glacier, we found a number of stones that were battered and worn and exhibited planed and scratched surfaces, in many respects similar to the glaciated stones found in the ancient moraines of New England. These occurred but a few feet from the ice foot, and their bruises and scratches are, without question, the work of the present glacier.

Glacier Movements. — That the small ice bodies of the Sierra Nevada have a true glacial motion is apparent from the nature of the crevasses and the curved courses of the dirt bands that cross them. Measurements of the movements of these glaciers have been made in only a few instances. The rate of the flow of the glacier on Mount McClure was determined by John Muir, who found that its maximum movement near the center was about 47 inches in 46 days (from August 21 to October 6, 1872). A more extended notice of these interesting observations is given in recording "previous observations" a few pages in advance.

Glacier Mud. — The Tuolumne river has its source at the foot of Lyell glacier. At its birth it is a rivulet, turbid with silt ground fine by the moving ice from beneath which it issues. At the foot of the Dana glacier there is a small lake confined in a rock basin, which has a peculiar greenish-yellow color due to silt held in suspension. The water escapes from this lake through a moraine piled on the rim of the basin, and is gathered again into other depressions farther down the cañon. The waters are thus filtered of matter in suspension, and the lower lakes are clear and blue, like hundreds of other lakelets and tarns scattered over the surrounding glaciated area. The sediment contributed to these glacial waters is so extremely fine that it requires days and perhaps weeks to settle.

Ice Tongues. — In the steep walls of the amphitheatres overlooking the névés of the glaciers here considered, there are frequently deep, narrow clefts leading toward the higher peaks. In many instances they are partially filled with ice, which shoots up above the névés in tapering

tongues some hundreds of feet in height and at so steep an angle that it is impossible to ascend or descend them without cutting steps. These ice tongues are interesting features of the Sierra glaciers and are also known to occur at the heads of similar ice streams in Wyoming. One of them, in the shadow of a precipice, is shown on Fig. A, Plate 2. Whether they have glacial motion or not, has never been determined. They appear to have originated from the freezing of waters flowing from adjacent areas, and not to have been formed entirely by the consolidation of névé snows, after the manner of true glacier ice.

Red Snow.—While Mr. Gilbert and myself were examining the névé portion of the Mount Lyell glacier, we noticed that our footprints in the snow had a bright pinkish tint, while the undisturbed surface appeared white or perhaps grayish white. At the lower border of the névé the color became more distinct and could be plainly seen in the untrodden snow, and in some instances the borders of rills were outlined by delicate pencilings of crimson. In all cases the "red snow" was superficial, or at most only covered by a thin layer of fresh snow. Some of the coloring matter collected was examined under the microscope a number of months later and found to consist of red globules from 150 to 200 millimeters in diameter, which were determined to be the minute algae known as *Protococcus.*

Surface Melting.—Our examination of Mount Lyell glacier began one August morning before sunrise, when the vast amphitheatre in which the ice is cradled was hushed in the profound stillness peculiar to mountain tops. As the sun rose above the granite spires to the eastward and flushed the snow fields with a ruddy light, little rills started here and there on the glacier, gradually gathering strength as the sun's warmth increased, and by noon brooks of considerable size were rushing down channels of ice, but sooner or later they plunged into crevasses and were lost to sight. At midday the murmur of water was heard everywhere over the glacier. As the chill of evening came on the music of the streams gradually ceased, and by sunset a death-like silence reigned over the frozen region.

That this noonday melting has more than counterbalanced the annual additions received during the years previous to our visit, seems evident from accounts of the former extent of the snow fields of the High Sierra. The observations bearing upon this point are given below. From

all that has been learned concerning the fluctuations of the glaciers of California, it appears that like those of Switzerland, they are subject to periodic changes, due principally to climatic oscillations. Since their discovery they have apparently not been increasing.

Pioneer Explorations in the High Sierra.

Although giving precedence to my own observations in describing the glaciers of the High Sierra, it is not my intention to ignore the reports of those who preceded me in the same field.

John Muir.—An anonymous article on the "Living Glaciers of California," which appeared in the Overland Monthly for December, 1872, and now known to have been from the pen of John Muir, is, so far as I can learn, the first announcement of the existence of glaciers on the Sierra Nevada. Mr. Muir states that in October, 1871, he was among the mountains of the Merced group and found a living glacier, with very recent moraines at its foot, from beneath which issued a stream of turbid water. Further observations revealed dirt bands, crevasses, and lateral moraines, thus leaving no doubt that the "snow bank," as it had previously been considered, was an actual glacier. Other similar ice bodies were examined by Mr. Muir, on Mount Lyell and Mount McClure ; and from the top of the former peak he saw a dozen snow and ice filled cirques on neighboring mountains.

In August, 1872, Mr. Muir placed five stakes in the glacier on Mount McClure, for the purpose of demonstrating whether or not it had true glacial motion. Four of these stakes were ranged in line from the east side to a point near the middle of the glacier, the first being 25 yards from the east bank ; the second, 94, the third, 152, and the fourth, 225 yards respectively. On observing the stakes on October 6, forty-six days after being placed in position, it was found that No. 1 had been carried down the glacier 11 inches ; No. 2, 18 inches ; No. 3, 34 inches ; No. 4, 47 inches. Stake No. 4 was near the middle of the glacier, and its displacement was thought to indicate the maximum motion of the ice. Stake No. 5 was placed about midway between the head of the glacier and No. 4. Its motion was 40 inches in forty-six days. These measurements, though not as detailed and perhaps not as accurate as could be desired, are yet sufficient to demonstrate, as claimed by Mr. Muir, that the ice in this instance had true glacial motion. In this example, as in

most normal glaciers, the greatest movement was near the middle of the ice stream.

The Mount McClure glacier, when visited by Mr. Muir, was approximately half a mile long and of about the same breadth in the widest part, and was observed to be traversed in the southeast corner by crevasses several yards long, but only about a foot wide. The Mount Lyell glacier, in 1872, is stated to have been about a mile in length by a mile in breadth.

Mr. Muir also describes narrow, high-grade cañons, called "devil's slides," "devil's lanes," etc., which occur about the higher peaks and are frequently occupied by ice. In one of these gorges the ice was found to have a motion of a fraction of an inch a day. These small ice bodies are what I have called "ice tongues" in describing my own observations. It is to be hoped that further information concerning their origin and behavior may be obtained, since, so far as is known, they do not appear in more heavily glaciated regions.

In an article entitled, "In the Heart of the California Alps,"[1] Mr. Muir gives some account of the glaciers about Mount Ritter, combined with enthusiastic descriptions of the magnificent scenery of the Sierra. In another article from the same pen on "Living Glaciers of California,"[2] several illustrations of glacial scenery are introduced, together with popular descriptions of numerous névés and ice fields.

Joseph Le Conte.—Professor Joseph Le Conte visited the High Sierra during the summers of 1872 and 1873, and in company with Mr. Muir examined the summit of Mount Lyell.[3] In describing the records of the ancient glaciers that once filled the Tuolumne valley, Le Conte says, that what interested him far more than anything else seen during his journey "was that on the main branch of the Tuolumne river, far up among the cliffs and peaks of Mount Lyell, *still exists a living glacier*, in a feeble state of activity, it is true, but certainly living." Professor Le

[1] Scribner's Monthly, vol. 20, 1880, p. 345.

[2] Harper's Magazine, vol. 51, 1875, p. 769. A brief account of the discovery of glaciers in the Sierra Nevada, and of some of their more prominent features, may be found in a charming book by John Muir, entitled "The Mountains of California," London, 1894.

[3] A portion of the observations made during these journeys was published in a paper, "On some of the Ancient Glaciers of the Sierra," Proceedings of the California Academy of Sciences, vol. 4, 1872, p. 159; and also in a more extended form, in the American Journal of Science, Third Series, vol. 5, 1873, p. 325. See also Le Conte's "Elements of Geology," revised edition, 1882, p. 602.

Conte accepts Mr. Muir's measurement, and concludes that "*the glacier motion still exists.*"

Mount Lyell glacier appears to have been more completely hidden by snow when examined by Le Conte in 1872 than when seen by the present writer ten years later. Le Conte's account, from the American Journal of Science, referred to above, is as follows :

" Here, then, on Mount Lyell, we have now existing, *not a true glacier*, perhaps, certainly *not a typical glacier* (since there is no true glacier ice visible, but only snow and névé, and certainly *no protrusion of an ice tongue beyond the snow field*), yet, nevertheless, *in some sense a glacier*, since there is true differential motion and a well-marked terminal moraine. It is, in fact, a glacier in feeble old age, a feeble remnant of the Tuolumne glacier, a glacier once of great proportions and playing an important part in mountain sculpture, but now in its second childhood."

Le Conte found the surface of the snow on the névé of the Lyell glacier "traversed in a direction at right angles to the slope by *sharp blades* of half-compacted ice about two feet apart and two, three, four, or even five feet in height; . . . the crests of the blades were not continuous, but irregular, both in outline and trend, very much in this respect like ripple marks or like waves."[1] The explanation offered — suggested by Mr. T. C. Gardner—is that the blades are due to the action of the sun on wind-ripples formed on the surface of the névé.

Geological Survey of California.—In the publication of the Geological Survey of California, no mention is made of existing glaciers in the Sierra Nevada. The frontispiece of Volume 1 (Geology), showing Mount Lyell as seen from Tuolumne valley, and also a sketch of the summit of the peak, forming Figure 73, indicate that the mountains were then far more heavily mantled with snow than in 1882 and 1883. Professor J. D. Whitney, formerly State Geologist of California, in his work on "Climatic changes of later geological time,"[2] says, "It may be stated that there are no glaciers in the Sierra Nevada proper and none in the Great Basin or Rocky Mountain ranges, at least south of the parallel of 42°. With the exception of some recent discoveries said to have been made in 1878, in the Wind River range (about latitude 43°) by the U. S. Geological Surveying party, of which no definite account seems as yet to have been pub-

[1] American Journal of Science, Third Series, vol. 5, 1873, p. 332.

[2] Memoirs of the Museum of Comparative Zoölogy of Harvard College, vol. 7, 1882, no. 2, p. 25.

lished, it may be stated that there are no proper glaciers anywhere within the limits of the United States (Alaska not included) except around the great isolated volcanic cones of the Pacific coast. There are certainly none in the higher portions of the Sierra Nevada or the Rocky mountains, these most elevated regions having been sufficiently explored to ascertain that fact." It will be noticed that this passage was published in 1882, or ten years later than Muir's and Le Conte's observations cited above. On page 30 of Professor Whitney's work, the notes of Messrs. King and Gardner made in 1868, while exploring the eastern slope of Mount Ritter, are transcribed as follows: "In a deep *cul-de-sac* which opens southward on the east slope [of Mount Ritter] lies a bed of ice 200 yards wide and about half a mile long. It has moved down from the upper end of the gorge for 30 or 40 feet this year, leaving a deep gulf between the vertical stone wall and the ice." In connection with these observations Professor Whitney remarks that "it is doubtful whether these residual masses of ice can with propriety be called glaciers."

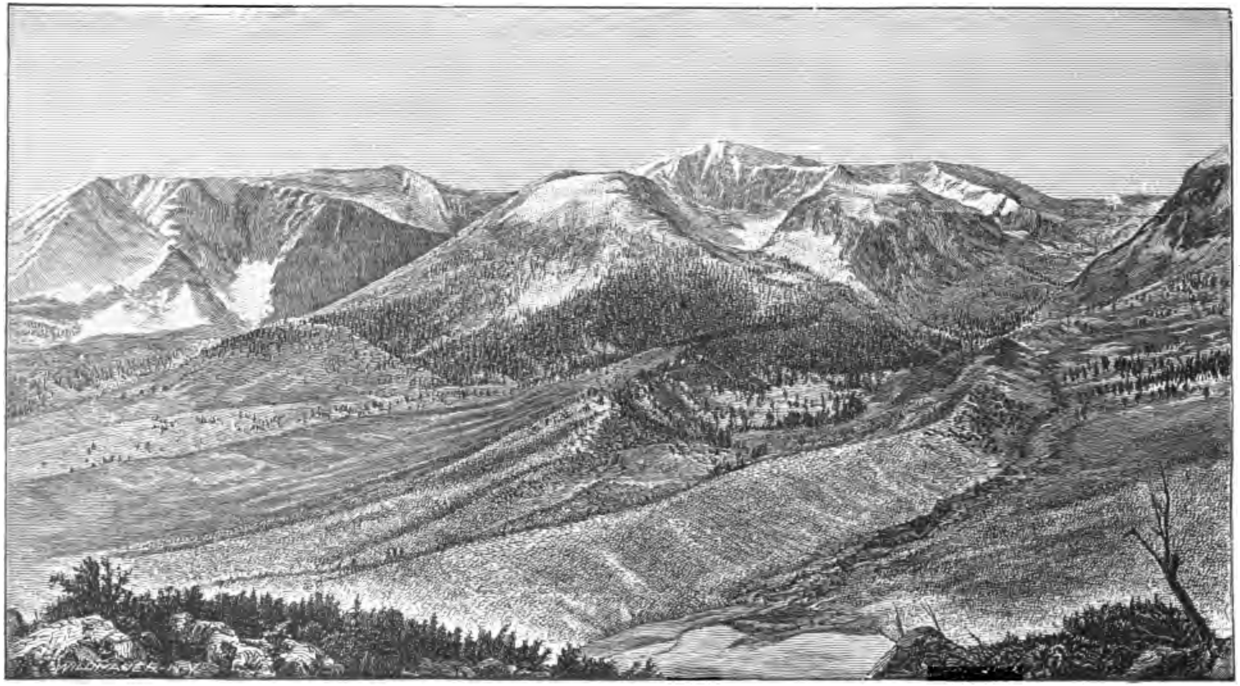
Clarence King. — Mr. King also rejected Mr. Muir's observations, as is shown by several emphatic passages in his Report of the Exploration of the 40th Parallel,[1] but adds no new information on the subject.

Conditions Favoring Observation. — From these quotations it will be seen that the question of the existence of glaciers in the Sierra Nevada has been decided differently by different observers, who perhaps saw the mountains under diverse conditions as regards their snowy covering. In winter the glaciers are so deeply snow-covered that no one would suspect their existence; it is only late in summer, when the snows have decreased to a minimum, that they are to be seen to the greatest advantage. That Mr. Muir was correct in classing many of the snow masses among true glaciers, has been sustained by recent studies, but the observations on which his decision was based, were not sufficiently extended to convince several geologists who visited the mountains when more completely snow-covered than at the time the measurements referred to above were made.

Ancient Glaciers.

It is necessary in the present volume to restrict attention to living glaciers, but in passing, I may mention that all of the higher portions of the Sierra Nevada, excepting the very highest peaks and crests, were

[1] Vol. 1, pp. 447, 448.



MORAINAL EMBANKMENTS AT THE MOUTH OF BLOODY CAÑON, MONO VALLEY, CALIFORNIA.

A map of these embankments may be found in the 8th Ann. Rep., U.S. Geol. Surv., Plate XXXV.

loaded with snow during the glacial period, so as to form a vast névé from which large ice streams flowed in various directions. The glaciers that went westward were far larger than those that descended the precipitous eastern escarpments. In several instances the ancient glaciers were majestic rivers of ice 30 or 40 miles long. The present ice bodies are the shrunken remnants of these ancient ancestors, or else mark the beginning of a new cycle, the former glaciers having been completely melted.

In the High Sierra to the westward of Mono lake, the more pronounced topographical features resulting from the ancient glaciation are conspicuously displayed. The broad-bottomed valley leading northward from Mount Lyell was formerly occupied by the great Tuolumne glacier. This received an important tributary from the region about Mount Dana, the path of which is deeply engraved in the topography of the country. The glacier formed by the union of these two ice streams flowed down the Tuolumne cañon for 30 or 40 miles, with a depth of between 2000 and 3000 feet; and it is believed to have occupied the Hetch-Hetchy valley, but its full extent is not known. Other magnificent glaciers having their sources about Mount Lyell and Mount Ritter descended the Merced and San Joaquin valleys, which, like the Tuolumne cañon, were greatly modified by ice erosion. To the eastward of the divide between the drainage to the Pacific and the Great basin, the paths of the ancient glaciers are definitely recorded by the smoothed and rounded contours of the valley, they occupied. Their channels are frequently fringed with lateral moraines, which in some instances were carried beyond the mouths of the cañons and prolonged upon the plain as parallel embankments. This feature is especially illustrated by the moraines at the mouths of Bloody, Parker, and Rush Creek cañons in Mono valley. At Bloody cañon and Parker creek two separate extensions of the glaciers are recorded by the morainal embankments. The glacier that flowed down Bloody cañon at first advanced upon the plain with a slight deflection to the right and built out a pair of huge morainal embankments; subsequently the ice retreated at least as far as the mouth of the cañon, and then advanced a second time with a deflection to the left, *i.e.* northward, and formed a pair of parallel embankments, still larger than the first. Two similar advances of the Parker Creek glacier are recorded by the very perfect morainal embankments still remaining. The ice stream which formerly occupied the valley of Rush creek was by far the largest that entered the Mono basin, and left many features of interest. As shown by smoothed

rock surfaces and by well-preserved moraines, this glacier was over 1500 feet thick where it left the cañon; before reaching the plain it was divided by a high rocky spur into two branches. The more southern branch deposited terminal moraines in such a way as to obstruct the outlet of the valley and cause a reversal of the stream when the glacier melted.

The evidence left by ancient glaciers in the Sierra Nevada is a part of the records of a Great Ice age found throughout the northern half of North America and in many other parts of the world, and falls properly in a history of Pleistocene times. The records of this history can be properly understood only by comparing them with similar inscriptions now being made. The study of existing glaciers is thus a preparation for the still greater task of deciphering the records of periods of ancient glaciation.

CHAPTER IV.

GLACIERS OF NORTHERN CALIFORNIA AND THE CASCADE MOUNTAINS.

THE Sierra Nevada is considered as terminating at the northward near the northern boundary of California; but whether this is in reality the limit of the disturbance that elevated the range remains to be positively determined. The same great series of mountains so pronounced in northern California is continued northward as a prominent topographical feature, through Oregon and Washington far into British America. North of California the chain had received the name of the Cascade mountains, and, unlike the Sierra Nevada, is largely composed of lava sheets. The volcanic overflows commence southward from what is generally considered as the southern extremity of the Cascade range, and form the grandest peaks in northern California. When the region is better known, perhaps the more southerly peaks will be classed in the same group as Tacoma, Jefferson, Hood, etc. These grand cones, the glory of the Northwest coast, have been but imperfectly explored, yet enough is known to assure us that many of them are glacier-crowned.

MOUNT SHASTA.

(A map of the glaciers on Mount Shasta is given on Plate 5.)

Observations by Clarence King.—The earliest account of the glaciers of Mount Shasta is given by Clarence King, who in company with several members of the U. S. Geological Exploration of the 40th Parallel, ascended the peak in September, 1870. From a report[1] of this pioneer climb, I have transcribed the portion relating to glaciers:

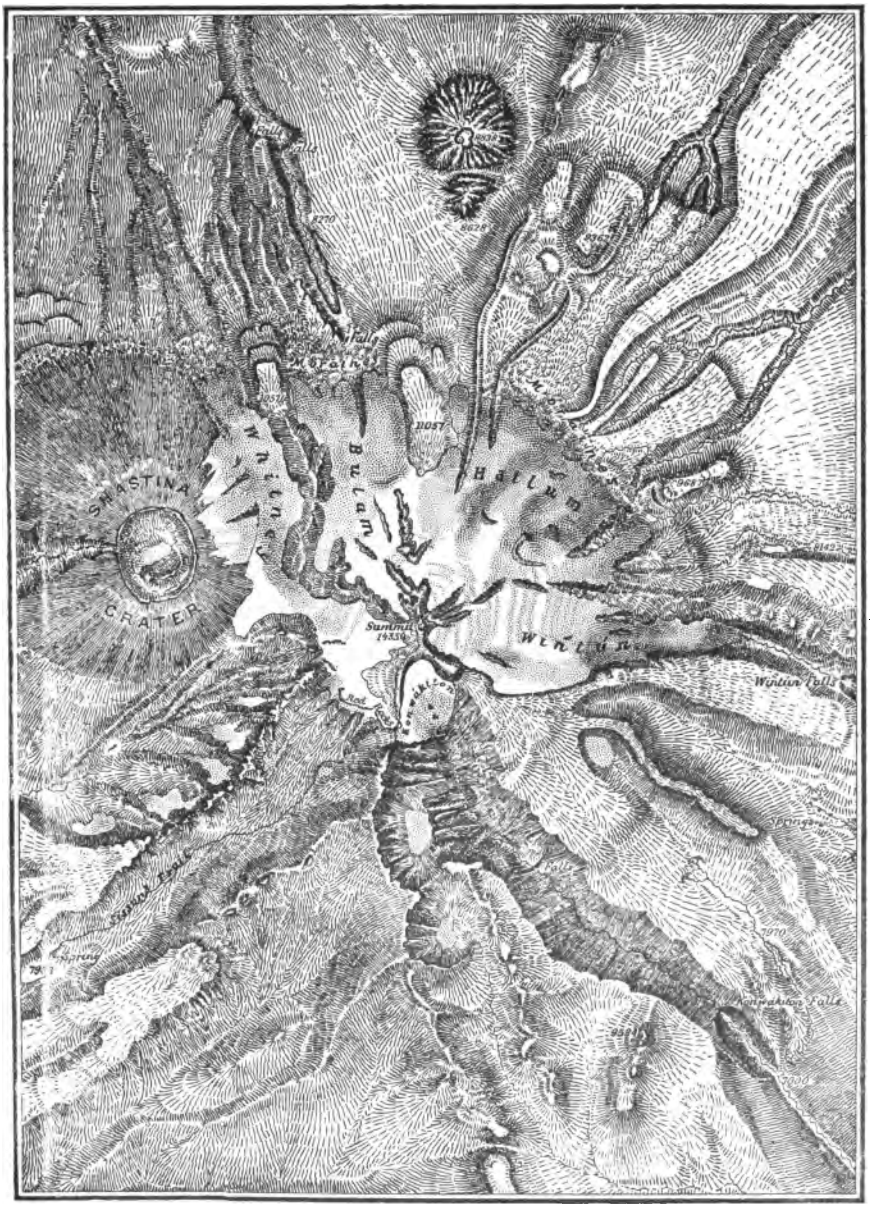
"On September the 11th, we climbed to the top of the lesser Shasta [named Shastina crater on Plate 5], a conical secondary crater jutting out from the main mass of the mountain on its northwest side. . . . We

[1] American Journal of Science, Third Series, vol. 1, 1871, p. 157. A more popular account was published in "Mountaineering in the Sierra Nevada," by the same author.

reached the rim of the cone, and looked down into a deep gorge lying between the secondary crater and the main mass of Shasta, and saw directly beneath us a fine glacier [since named Whitney glacier; see Plate 5 and Figure A, Plate 6], which started almost at the very crest of the main mountain, flowing towards us, and curving around the circular base of our cone. Its entire length in view was not less than three miles, its width opposite our station about 4000 feet,[1] the surface here and there terribly broken in 'cascades,' and presenting all the characteristic features of similar glaciers elsewhere. The region of the terminal moraine was more extended than is usual in the Alps. The piles of rubbish superimposed upon the end of the ice indicated a much greater thickness of the glacier in former days. After finishing our observations upon the side crater and spending a night upon the sharp edge of its rim, on the following morning we climbed over the divide to the main cone, and up to the extreme summit of Shasta, a point 14,440 feet above the sea level. From the crest I walked out to the northern edge of a prominent spur and looked down upon the system of three considerable glaciers, the largest about four and one-half miles in length and two or three miles wide. On the next day we descended on the south side of the cone, following the ordinary track by which earlier parties have made the climb. From the moment we left the summit we encountered less and less snow, and at no part of the journey were we able to see a glacier. An east and west line divided the mountain into glacier-bearing and non-glacier-bearing halves. The ascent was formerly made upon the north side, where, as stated, there are no glaciers, and this is why able scientific observers, like Professor Whitney and his party, should have scaled the mountain without discovering their existence.

"Before and after the ascent of Mount Shasta, a week was given for an examination of the southern half of the volcano. Since the earliest settlement of Strawberry and Shasta valleys, there has never been such a complete denudation. From June to November the snow masses were less than they have ever been seen before. This favored greatly our geological observations, and gave us an excellent opportunity to study the relics of the former great névé. We explored one after another all the cañons, which, approximately following the radius of the cone, are carved to a greater or less depth into the lava flows. From the secondary cone around

[1] J. S. Diller states that this glacier varies from 1000 to 2000 feet in width, and has a length of two and one-fifth miles. National Geographic Monographs, vol. 1, 1895, p. 259.



SKETCH MAP OF MOUNT SHASTA, CALIFORNIA, BY GILBERT THOMPSON.

Scale: 1 inch = 10,200 feet.

the eastern side of the main mass are only occasional fields of snow, and ice bodies of a thousand or two feet long, usually quite narrow and lying on the more shaded sides of the ravines. In nature and texture they are quite similar to the true glacial ice, possessing in all cases planes of stratification, which indicate the pressure of the formerly overlying masses. There is little doubt that all the scattered snow fields that in the months of August and September dapple the southern slopes are the relics of glaciers. They are found in the region of the ancient névé, but extending downward into what was formerly the zone of movement.

"Upon reaching the eastern side we found in a deep cañon a considerable glacier, having its origin in a broad névé which reached to the very summit of the peak. The entire angle of this glacier can hardly be less than 28°. It is one series of cascades, the whole front of the ice being crevassed in the most interesting manner. Near the lower end, divided by a boss of lava, it forks into two distinct bodies, one extending in an abrupt, rounded face, no less than 900 feet in height. Below this another branch extends down the cañon for a mile and a half, covered throughout almost in entire length with loads of stones which are constantly falling in showers from the cañon walls on either side. Indeed for a full mile the ice is only visible in occasional spots where cavities have been melted into its body and loads of stones have fallen in. From an archway under the end a considerable stream flows out, milky, like the waters of the Swiss glacier streams, with suspended sand. Following around the eastern base of Shasta, we made our camps near the upper region of vegetation, where the forest and perpetual snow touch each other. A third glacier of somewhat greater extent than the one just described was found upon the northeast slope of the mountain, and upon the north slope one of much greater dimensions. The exploration of this latter proved of very great interest in more ways than one. Receiving the snow of the entire north slope of the cone, it falls in a great field covering the slope of the mountain for a breadth of about three or four miles, reaching down the cañons between four and five miles, its lower edge dividing into a number of lesser ice streams which occupy the beds of the cañons. This mass is sufficiently large to partake of the convexity of the cone, and judging from the depth of the cañons upon the south and southeast slopes of the mountain, the thickness cannot be less than from 1800 to 2500 feet. It is crevassed in a series of immense chasms, some of them 2000 feet long by 30 and even 50 feet wide. In one or two places the whole surface is broken

with concentric systems of fissures, and these are invaded by a set of radial breaks which shatter the ice into a confusion of immense blocks. Snow bridges, similar to those in the Swiss glaciers, are the only means of crossing these chasms, and lend a spice of danger to the whole examination. The region of the terminal moraines is quite unlike that of the Alps, a larger portion of the glacier itself being covered with loads of angular débris. The whole north face of the mountain is one great body of ice interrupted by a few sharp lava ridges which project above its general level. The veins of blue ice and the planes of stratification were distinctly observed, but neither *moulins* nor regular dirt bands are present. Numerous streams, however, flow over the surface of the ice, but they happen to pour into crevasses which are at present quite wide.

"One of the most interesting of all the features of the country was, however, the clearly defined moraines of the ancient and more widely extended glacier system. Nearly the whole topography of the lower part of the cone is modified by the deposition of glacial material. At an elevation of about 8000 feet upon the northern or snowless side of the mountain is a great plateau-like terrace, 2500 or 3000 feet wide, extending around one-half of the cone and composed wholly of morainal material. Besides these, long straight or slightly curved medial moraines jut from the mountain in all directions, not unfrequently descending into the valley for several miles."

A brief account of the glaciers of Mount Shasta was contributed by King to an article on gravel ridges in Merrimack valley, New Hampshire, from the pen of G. F. Wright,[1] in which special attention is given to the moraines now forming on the margins of the glaciers and their resemblance to certain glacial deposits of New England.

In the account of an ascent of Mount Shasta, published in the reports of the Geological Survey of California,[2] of which Professor J. D. Whitney was director, no mention is made of the existence of glaciers. In Professor Whitney's recent work, "Climatic Changes of Later Geological Time," previously referred to, an account of these glaciers is introduced, but it contains no observations in addition to those already published by King.

Observations by Gilbert Thompson.—In 1882, a topographical survey of the region about Mount Shasta was begun by Gilbert Thompson,

[1] Boston Soc. of Nat. Hist., Proc., vol. 19, 1876, p. 60.
[2] Vol. 1 (Geology), pp. 332-351.

of the U. S. Geological Survey, who, at my request, kindly furnished the following notes and accompanying sketch map, which form a valuable addition to the previous descriptions of the mountain:

"During a portion of the season of 1883, I was engaged in obtaining the topographical details of Mount Shasta, California, and take pleasure in furnishing such information as I can concerning the glaciers now existing on the mountain.

"Mount Shasta is a volcanic peak situated in latitude 41° 24′ 30″, longitude 122° 11′ 34″. Its altitude, as determined by the U. S. Geological Survey, is 14,350 feet. It stands alone and has no connection with neighboring mountains, none of which within a radius of 40 miles attain two-thirds its height. The greatest length of its northwest slope, terminated by Little Shasta valley, which has an altitude of 3000 feet, is 16 miles. The southwest slope reaches Elk flat and descends over 10,000 feet in eight miles. The highest divide to the northwest is six miles distant and has an altitude of 6000 feet. The divide of the Sacramento river, ten miles to the westward, is 3500 feet above the sea. The ordinates from the summit to the contour of 8000 feet will vary from three to four miles in length. The point where the timber growth receives its first check is at an elevation of 8200 feet; the last tree, however, so diminutive as hardly to cover the palm of one's hand, was found at the altitude of 10,130 feet. Mount Shasta attracts the attention at a distance of over 100 miles, and from nearer points the solemn repose and grandeur of its isolation are impressive.

"The glaciers about the summit of Mount Shasta do not exist under the protection of sheltering cliffs or in the depths of cañons, but occur on the flanks of the mountains and are exposed for three-fourths of the day to the full power of the sun. The streams that have their origin in the melting of the snow, appear suddenly at the foot of the mountain as rushing currents loaded with silt; these subside during the latter part of the night and leave pools of clear water, which also gradually disappear. The water again reaches the surface in unexpected places many miles distant as immense springs. The stream channels are thus flooded once a day during the summer; and after the first snow, which occurs about the first of October, no more water descends from the snow fields.

"Besides a few snow banks that last throughout the year and a few small glaciers in the shadow of protecting cliffs, there are five ice streams which especially invite attention. With the exception of the Whitney glacier, which was named in honor of the former state geologist of

California, these have been designated by the following Wintun names: Konwakiton (mud glacier), Wintun (Indian tribal name), Hotlum (Steeprock), and Bulam (great).

"The Konwakiton [McCloud] glacier is situated on the southeastern slope and fills a basin at the head of a deep and rugged cañon. Its foot is at the altitude of about 12,000 feet, and from beneath it a strong stream flows down the gorge, at times disappearing beneath a flooring of ice, covered with boulders and débris derived from the walls that overshadow it. On reference to the topographic sketch [Plate 3] it will be seen that this stream falls in a cascade in the upper portion of the cañon; at a lower altitude it forms another beautiful waterfall about 400 feet in height. The surface of this glacier has an area of about 320,000 square yards. When making the ascent by Sisson's southern foot-trail, just as the weary climber turns the 'Red rocks,' at 13,000 feet altitude, he is forced to make a short detour on the névé of this glacier, which is usually separated from the wall of rock by a deep crevasse.[1]

"The Wintun glacier has an area of about 2,000,000 square yards, an average breadth of 1000 yards, and is 3400 yards in length. In its course it flows over two precipices and becomes greatly broken by curving crevasses, inclosing huge rocks and pinnacles of ice. These are veritable ice cascades of no mean proportions, and afford details of glacial structure of great beauty and interest. Near its terminus the glacier forms a true ice stream confined by cañon walls, and finally terminates in an ice foot several hundred feet high which, as indicated in the accompanying sketch, is furrowed by numerous stream-cut channels. A close approach to the ice wall is dangerous because of the stones and morainal matter that at least in summer are constantly falling as the ice melts. The glacier terminates at an altitude of about 8000 feet, and from it flows a considerable stream which is always loaded with mud and silt. Some distance below the terminus this yellow stream forms a cascade fully 400 feet in height. The walls of the cañon occupied by the lower

[1] In describing this glacier J. S. Diller states that the morainal material upon its borders is small, and yet, of all the glaciers about Mount Shasta, it is the only one which has left a prominent record of important changes. During a former period it was over five miles in length and occupied an area of at least seven square miles, being twenty times its present size. With this exception, there are no records upon the slopes of Shasta that any of the existing glaciers were ever very much larger than at present.

The existing glaciers on Mount Shasta are but remnants of far larger ice streams that descended from the mountain in Pleistocene time, and left large and well-characterized moraines on its southwestern side some ten miles from the summit. National Geographic Monographs, vol. 1, 1895, pp. 262, 263.

portions of this glacier, in common with nearly all the flanks of Mount Shasta, are sombre in color and unpicturesque; below the falls, however, there are many points of view that will hold the attention and excite the enthusiasm of the traveler.

"The Hotlum glacier[1] is situated northward of the Wintun, and separated from it by a series of narrow and precipitous spurs. On the north it is bounded by a narrow crest of rock which at first glance might be taken to be a medial moraine. The foot of this glacier ends in an arc of terminal moraines, at an altitude of 10,500 feet, which at certain points rests upon the lower portion of the ice. A thousand streams formed by the melting glacier find their way over and through the débris field, and render it a treacherous terrain to explore.

"Through the névé of the Hotlum glacier two ice streams may be said to flow, one of which, in crowding past two rocky buttresses, is broken into pinnacles of ice 50 to 60 feet in height, which are of a pearly blue tint, and present a fantastic and beautiful spectacle. The crevasses below the rocks are very deep and wide. Associated with them are wells of water of great depth having a translucent blue color; these were oval in shape, the longer axis being in the direction of the flow of the glacier. The glacier is 2500 yards in length, and covers an area of about 3,200,000 square yards.

"The Bulam glacier, situated on the northern face of the mountain, indicates by the magnitude of its terminal moraine that it carries greater floods of débris than any of its associated ice streams. At the time of my examination the foot of this glacier had retreated to a considerable distance from the terminal moraines, and was divided into two flows. The first crevasse in this glacier occurs at an elevation of about 11,000 feet, and is of great width, length, and depth. From this rent to the terminus of the glacier the ice is broken into rough blocks, and is deeply seamed with fissures. The Bulam glacier is about 3200 yards in length, and approximately 1,800,000 square yards in area. The crest of the terminal moraine skirting its lower limit had an altitude of 10,000 feet.

"Separated from Bulam glacier by a steep, narrow ridge, as represented on Plate 5, is Whitney glacier, a photograph of which is given in Fig. A, Plate 6. This is the most typical ice stream on the mountain, and originates in the névé lying on the table at the summit of

[1] The surface of the Hotlum glacier is convex from side to side, and its width (1.23 miles) is almost as great as its length (1.62 miles). J. S. Diller, National Geographic Monographs, 1895, vol. 1, p. 261.

the peak. Whitney glacier, in crowding past the east base of Shastina crater, which it has partially undermined, occasions a constant falling of rocks and débris, and becomes broken into a multitude of blocks, which are reunited as the stream flows on. The Whitney glacier is 3800 yards in length, and covers an area of 1,900,000 square yards; in October, 1883, its terminus was at an elevation of 9500 feet above the sea.[1]

"A careful examination of some of the ice bodies on the western flank of Mount Shasta would perhaps lead to their being classed as glaciers of secondary magnitude; they occur on steep slopes at high altitudes, and all are over 700 feet in length.

"At the time of Mr. King's examination, in 1870, Mr. Watkins, of San Francisco, obtained a number of photographs of Mount Shasta, from a careful examination of which I conclude that there was more snow on the mountain when they were taken than at the time of my visit in 1883; this decision is also sustained by the statements of the residents in the vicinity."[2]

Mount Rainier.

(A sketch map of the glaciers on Mt. Rainier forms Plate 7.)

In the Proceedings of the California Academy of Sciences for March 6, 1871, it is stated by Professor George Davidson that Lieutenant, afterward General, August V. Kautz attempted the ascent of Mount Rainier in 1857, but found his way barred by a great glacier. So far as can be ascertained no published account of Kautz's observations has appeared, but from Davidson's statement it seems that he first reported the existence of living glaciers in the United States. An abstract of Kautz's manuscript account of his excursion is given by S. F. Emmons[3] in an

[1] "The most striking feature of Whitney glacier, and that which is of the greatest interest from a geologic point of view, is the débris it brings down the mountain and piles up, making a large terminal moraine at its lower end. This moraine appears to be fully a mile in length, measured down the slope of the mountain. Its apparent length is much greater than the real, however, from the fact that the glacier ice extends far beneath the covering of detritus. It is so huge a pile of light-colored débris, just above the timber line, that it is plainly visible from afar." J. S. Diller, National Geographic Monographs, vol. 1, 1895, pp. 259, 260.

[2] Since the book before you was written, an instructive monograph on "Mt. Shasta, a Typical Volcano," has been published by J. S. Diller, which includes an account of the glaciers described above. The book referred to is one of a series entitled "National Geographic Monographs," published under the auspices of the National Geographic Society.

[3] Journal of the American Geographical Society, vol. 9, p. 45.

FIG. A.—WHITNEY GLACIER, MOUNT SHASTA, CALIFORNIA.

FIG. B.—SUMMIT OF MOUNT RAINIER, WASHINGTON.

The head of Emmons Glacier. Little Tahoma and Gibraltar on the left.

address before the American Geographical Society, but it contains little information of special interest concerning the glacier seen.

Observations by S. F. Emmons. — The address referred to above, entitled "The Volcanoes of the Pacific Coast of the United States," is devoted mainly to a description of an ascent of Mount Rainier by Emmons in October, 1870, and includes many observations on the glaciers examined during his survey of the mountain. A more detailed account of these glaciers was contributed by Emmons to an article by King[1] on the glaciers of the Pacific slope, and I shall quote from this in preference to the more popular essay read before the Geographical Society:

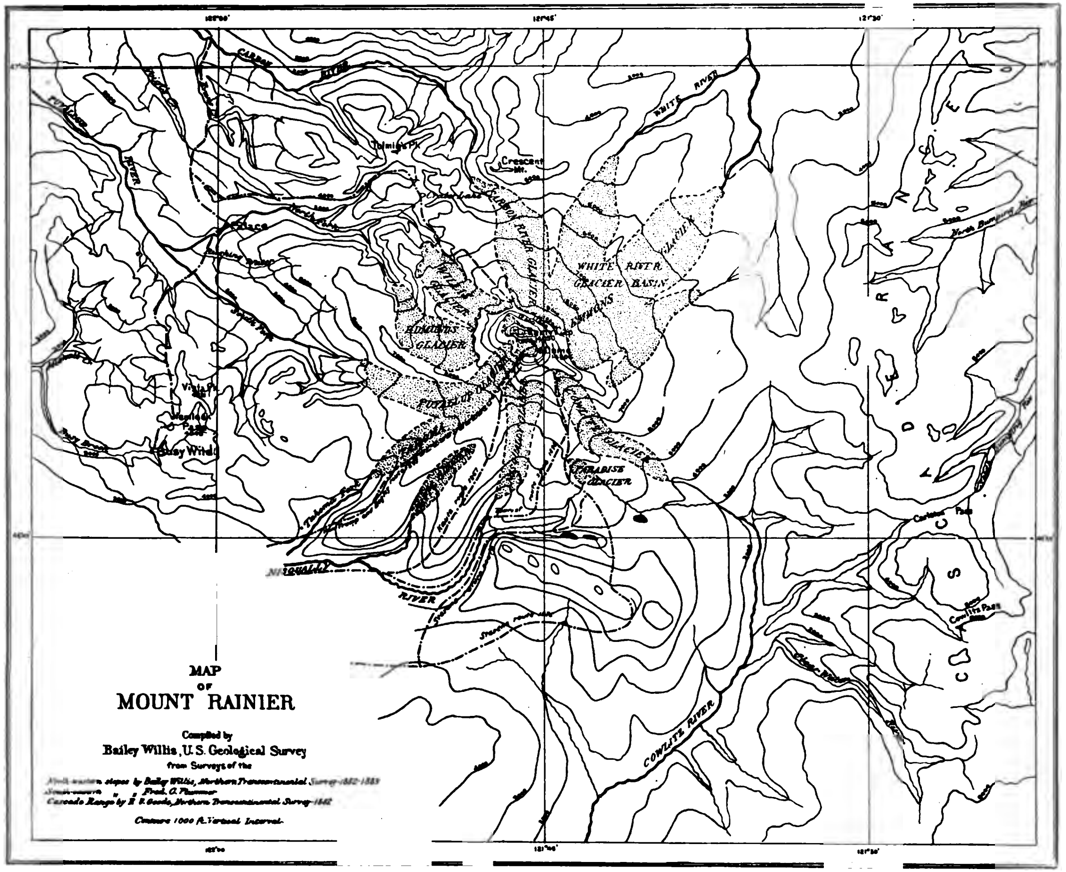
"The glaciers of Mount Tachoma [Tacoma], or Rainier, as it is more commonly called, form the principal sources of four important rivers of Washington Territory, *viz.*: the Cowlitz, which flows into the Columbia, and the Nisqually, Puyallup, and White rivers, which empty into Puget sound. . . . The summit of Tachoma is formed by three peaks, a southern, an eastern, and a northwestern; of these the eastern is the highest; those on the south and northwest, being apparently a few hundred feet lower, are distant about a mile and a half to two miles from this, and separated by deep valleys. The eastern peak which would seem to have formed originally the middle of the mountain mass, is a crater about a quarter of a mile in diameter of very perfect circular form. Its sides are bare for about sixty feet from the rim, below which they are covered by a névé having a slope of 28° to 31°. This névé, extending from the shoulders of the southwestern peak to those of the northern, a width of several miles, descends to a vertical distance of about 2000 feet below the crater rim, an immense sheet of white granular ice having the general form of the mountain surface, and broken only by long transverse crevasses, one of those observed being from one to two miles in length; it is then divided up by the several jutting rock masses, or shoulders of the mountain, into the Nisqually, Cowlitz, and White River glaciers, falling in distinct ice cascades for about 3000 feet at very steep angles, which sometimes approach the perpendicular. From the foot of these cascades flow the glaciers proper at a more gentle angle, growing narrower and sinking deeper into the mountain as they descend. From the intervening spurs, which slope even more gradually, they receive many tributary glaciers, while some of these secondary glaciers form independent streams which only join the main river many miles below the end of the glaciers.

[1] American Journal of Science, Third Series, vol. 1, 1871, p. 161.

"The Nisqually, the narrowest of the three main glaciers above mentioned, has the most sinuous course, varying in direction from southwest to south, while its lower extremity is somewhat west of south of the main peak; it receives most of its tributaries from the spur to the east, and has a comparatively regular slope in its whole length below the cascade. There are some indications of dirt bands on its surface when seen from a considerable elevation. Toward its lower end it is very much broken up by transverse and longitudinal crevasses; this is due to the fact that it has here cut through the more yielding strata of volcanic rock, and come upon an underlying and unconformable mass of syenite. The ice front [Fig. B, Plate 6] at its base is about 500 feet in height, and the walls of lava which bound its sides rise from 1000 to 1500 feet above the surface of the ice, generally in sheer precipices.

"The bed of the Cowlitz glacier is generally parallel to that of the Nisqually, though its curves are less marked; the ice cascades in which each originates fall on either side of a black cliff of bedded lava and breccia scarcely a thousand feet in horizontal thickness, while the mouths of the glaciers, if I may be allowed the expression, are about three miles apart. From the jutting edge of this cliff hang enormous icicles from 75 to 100 feet in length. The slope of this glacier is less regular, being broken by subordinate ice cascades. Like the Nisqually, its lower extremity stretches out, as it were, into the forest, the slopes on either side, where not too steep, being covered with the mountain fir, *Picea nobilis*, for several hundred feet above the level of the ice, while the *Pinus flexilis* grows at least 2000 feet higher than the mouth of the glacier.

"The general course of this glacier is south, but at its extremity it bends to the eastward, apparently deflected from its course by a cliff of older felsitic rock more resisting than the lava. The consequence of this deflection is a predominance of longitudinal over transverse crevasses at this point, and an unusually large moraine at its western side, which rises several hundred feet above the surface of the glaciers, and partakes of the character of both lateral and terminal moraines; the main medial moraine of a glacier joins this near its lower end. [The crevassed and moraine-covered surface of Cowlitz glacier is shown in Fig. A, Plate 8.] This medial moraine proceeds from the cliff which bounds the ice-cascade source of the glacier on the north, and brings down a dark porous lava which is only found high up on the mountain near the crater. The position of the medial moraine on the glacier would indicate that at



Approximate scale: one inch = seven miles.

least half its mass came from the spur on the east, which is probably the case.

"This spur, comprehending the whole mass between the Cowlitz and White River glaciers, has the shape of a triangle, whose apex is formed by a huge pinnacle of rock which, as its bedding indicates, once formed part of the crest of the mountain, but now stands isolated, a jagged peak rising about 3000 feet above the glaciers at its foot, so steep that neither ice nor snow rests upon it. One of the tributaries to the Cowlitz glacier from this spur brings down with it a second medial moraine, which is traceable to the mouth of the glacier, though in general these tributary glaciers bring no medial moraines.

"On the eastern slopes of this spur, between the two above-named glaciers, spread secondary glaciers frequently of great width, but, owing to the limited height of their initial points, of inconsiderable length. These end generally in perpendicular cliffs overhanging the rocky amphitheatres at the heads of the smaller streams which flow eastward into the Cowlitz. Looking up from the bottom of one of these amphitheatres one sees a semicircular wall of nearly 2000 feet of sheer rock, surmounted by about 500 feet of ice, from under which small streams of water issue, falling in silvery cascades onto the green bottom below.

"A ridge of high jagged peaks connects this spur with the main range of the Cascade mountains in the east, and forms the watershed between the White and Cowlitz rivers. From the connecting saddle one can look northward across the brink of six glaciers, which all contribute to the White river; of these the first four come from the triangular spur already mentioned, and are of comparatively little extent. The first two are, however, interesting from the veined structure which they exhibit; they both originate in an irregularly oblong basin, having the shape somewhat of an inclined ellipse, turning on its long diameter, the outlets of the glacier being opposite the foci. Seen from a high point the veins form concentric lines generally parallel to the sides of the basin; the ends of those towards the center gradually bend round until they join together in form of a figure S, and finally just above the outlets form two small ellipses. They thus constantly preserve a direction at right angles to that of the pressure exerted downward by the movement of the ice mass, and upward by the resistance to this movement of the rock mass between the two outlets.

"The main White River glacier, the grandest of the whole, pours straight down from the rim of the crater in a northeasterly direction, and

pushes its extremity farther out into the valley than any of the others. Its greatest width on the steep slope of the mountain must be four or five miles, narrowing towards its extremity to about a mile and a half; its length can be scarcely less than ten miles. The great eroding power of glacial ice is strikingly illustrated in this glacier, which seems to have cut down and carried away on the northeastern side of the mountain, fully a third of its mass. The thickness of rock cut away, as shown by the walls on either side, and the isolated peak at the head of the triangular spur, in which the bedding of the successive flows of lava is very regular and conformable, may be estimated at somewhat over a mile. Of the thickness of the ice of the glacier I have no data for making estimates, though it may probably be reckoned in thousands of feet.

"It has two principal medial moraines, which, where crossed by us, formed little mountain ridges having peaks nearly 100 feet high. The sources of these moraines are cliffs on the steeper mountain slope, which seem mere black specks in the great white field above; between these are great cascades, and below immense transverse crevasses, which we had no time or means to visit. The surface water flows in rills and brooks on the lower portion of the glacier, and *moulins* are of frequent occurrence. We visited one double *moulin* where two brooks poured into two circular wells, each about ten feet in diameter, joined together at the surface but separated below; we could not approach near enough the edge to see the bottom of either, but, as stones thrown in sent back no sound, judged they must be very deep.

"This glacier forks near the foot of the steeper mountain slope, and sends off a branch to the northward, which forms a large stream flowing down to join the main stream fifteen or twenty miles below. Looking down on this from a high, overhanging peak, we could see, as it were under our feet, a little lake of deep blue water, about an eighth of a mile in diameter, standing in the brown gravel-covered ice of the end of the glacier. On the back of the rocky spur which divides these two glaciers, a secondary glacier has scooped out a basin-shaped bed, and sends down an ice stream having all the characteristics of a true glacier, but its ice disappears several miles above the mouths of the large glaciers on either side. Were nothing known of the movements of glaciers, an instance like this would seem to afford sufficient evidence that such movement exists, and that gravity is the main motive power. From our northern and southern points we could trace the beds of several large glaciers to the west of us, whose upper and lower portions only were

FIG. A.—SURFACE OF COWLITZ GLACIER, MOUNT RAINIER, WASHINGTON.

FIG. B.—ICE CAVE AT THE END OF NISQUALLY GLACIER, MOUNT RAINIER, WASHINGTON.

visible, the main body of the ice lying hidden by the high intervening spurs.

"Ten large glaciers observed by us, and at least half as many more hidden by the mountain from our view, proceeding thus from an isolated peak, formed a most remarkable system, and one worthy of a careful and detailed study."

A graphic account of an ascent of "Takhoma" [Rainier] was published in the Atlantic Monthly[1] by General Hazard Stevens, who ascended the peak in August, 1870. Frequent references are made in this essay to the numerous ice streams that originate on the mountain, but no detailed account of glacial phenomena is presented.

Recent Ascents. — Since the pioneer ascents of Mount Rainier described above were made, the mountain has been ascended by many tourists, and now that the route to the summit is familiar it appears that the climb is not so difficult as at first supposed. Several excursion parties have succeeded in reaching the summit, and have even passed the night in the crater at the top. Ladies have been members of these expeditions and have experienced no great fatigue or hardship from their ascent. A graphic and entertaining account of one of the more recent ascents, by Rev. Ernest C. Smith, in which the luxuriance and beauty of the vegetation clothing the lower slopes of the majestic peak are contrasted with the barrenness and desolation of the snow fields at the summit, appeared in Appalachia,[2] and is accompanied by a number of excellent photographs of glaciers.

The magnificence of the scenery about Mount Rainier and in the neighboring Cascade mountains, as well as a widely spread popular interest in the glaciers and other natural features of that region, has led to an effort to have Congress set aside a reservation to be known as the Washington National Park, and embracing an area of about 25 miles square, of which the summit of Mount Rainier is the culminating point.

Mount Hood.

In August, 1866, Professor A. Wood ascended Mount Hood, and later in the year gave a short account of his observations before the California Academy of Sciences.[3] During his ascent he encountered chasms of

[1] Vol. 38, 1876, p. 513. [2] Vol. 7, 1894, pp. 185–205.
[3] Proceedings, vol. 3, p. 292.

invisible depth in solid blue ice, in which the rush of subglacial streams could be heard. From the summit of the peak a deep cañon, eroded in the steep southeast slope of the mountain, was seen to be partly filled by a glacier. Both terminal and lateral moraines could be distinguished on the surface of the ice, and a torrent of water issued from its terminus.

Observation by Arnold Hague. — In a contribution to King's article on the glaciers of the Pacific coast,[1] already referred to, the following account of the existing glaciers of Mount Hood is given by Arnold Hague:

"The crater [of Mount Hood] is nearly one-half a mile wide from east to west. The wall upon the inner side rises above the snow and ice filling the basin some 450 feet, while upon the outer side it falls off abruptly for 2000 feet. This rim of the crater is very narrow; in many places the crest is not more than 2 feet wide.

"Three distinct glaciers have their origin in this basin, each the source of a stream of considerable size; the glaciers of the White, the Sandy, and the Little Sandy rivers.

"The White River glacier heads on the eastern side of the crater and extends in a southeasterly direction. It is barely a quarter of a mile wide at the head, and about 2 miles long, extending 500 feet below the line of the timber growth upon the side of the mountain.

"Near the top of the crater a broad transverse crevasse cuts entirely across the glacier. Freshly fallen snow overhangs the perpendicular walls of ice, making it exceedingly dangerous to approach. At one point only the fissure may be crossed by an ice bridge. Further down the slope of the glacier transverse crevasses are of frequent occurrence, running nearly parallel with each other; most of them are, however, quite narrow. One broad chasm presented clean, sharply cut vertical sides, for nearly 200 feet in depth, of clear deep-blue ice. Marginal crevasses, ice caves, and caverns occur. Many of the latter are very beautiful and afford fine opportunities for the study of the laminated and veined structure of glacial ice.

"Very many of the phenomena attendant upon glaciers elsewhere may be observed here. The terminal and lateral moraines are well marked and extensive. Medial moraines, however, do not appear, because the glacier has no tributaries. Glacial grooving, glacial débris, and boulders are quite characteristic.

[1] American Journal of Science, Third Series, vol. 1, 1871, p. 165.

FIG. A.—SUMMIT OF MOUNT BAKER, WASHINGTON.

FIG. B.—CREVASSES, ILLECELLEWAET GLACIER, CANADA.

(Photograph by Wm. Notman & Son.)

"The glacier of Sandy river is separated from that of the White river by a high, bare ridge, standing boldly up above the ice and dividing the crater into two parts. The glacier descends to the southwest. It is fed by the snow and ice of a somewhat larger area of country, and is considerably broader than the glacier of White river. In length they are about equal.

"An immense amount of glacial débris must be annually carried down the streams whose waters are heavily charged with fine, light gray trachytic sand, brought down from above by this moving mass of ice. The character of the rock, a brittle, porous trachytic, is such that under the wearing action of the glacier it would be easily eroded and ground to fine powder. The very extensive accumulation of sand banks, which are constantly forming at the mouth of the stream where it empties into the Columbia river, bears ample evidence of the fact.

"The Little Sandy river, a tributary of the main stream, with which it unites a few miles below the base of the mountain, has its source in the third glacier which is formed on the western flank of the peak, separated from the Sandy by a high wall, a somewhat broken, irregular ridge of trachytic, which extends along the southwest slope of the mountain.

"The upper portion of the névé of the glacier is inclined at quite a high angle, and is considerably fissured by broad, deep crevasses. It has cut into the sides of the mountain a deep, narrow gorge, with bare, precipitous cliffs. The glacier and the valley of the Little Sandy are both quite narrow.

"One of the most marked geological and topographical features of Mount Hood and the vicinity is its very extensive system of extinct glaciers, which everywhere gouged out immense trough-shaped valleys, cutting down deeply into the earlier trachytic lava flow of the old volcano. The entire network of valleys was connected with two main glaciers, that of Hood river on the north and the Sandy on the south. The ancient White River glacier was undoubtedly very large, but, as far as my observations have yet extended, had no tributaries."

Mount Baker.

Mr. E. T. Colman, of the English Alpine Club, ascended Mount Baker in 1869. A popular account of this excursion appeared in Harper's Magazine,[1] in which snow fields, glaciers, crevasses, etc., are described in

[1] Vol. 39, 1869, p. 793.

such a manner as to indicate that glaciers of very considerable magnitude are now flowing down the mountain. The peak has since been ascended by several parties. The accompanying illustration of the summit of the mountain is from a photograph taken by Professor E. S. Ingraham, of Seattle, Washington, and shows that glaciers of conspicuous size may originate in unsheltered situations.

Glaciers on other Peaks of the Northwest.

Mr. J. S. Diller, of the United States Geological Survey, has made various reconnaissances and surveys from Mount Shasta northward to the Canadian boundary, and has observed glaciers of considerable magnitude on Mount Jefferson, Diamond Peak, the Three Sisters, and Mount St. Helens. Mount Scott and Mount Thielsen were found to be free from glacial ice. The group of peaks known as the Three Sisters is considered by Mr. Diller as probably affording the most interesting field for glacial studies in the United States, with the exception of Alaska. The glaciers amid this group of peaks attracted the attention of Dr. J. S. Newberry, while connected with the Pacific railroad surveys in 1855, but no report of his observations has been published.

When the lofty summits of the Cascade mountains are more thoroughly explored, it will undoubtedly be found that many more are glacier-crowned than have been reported up to the present time. The glaciers of the Cascade region are all of the alpine type, but are somewhat peculiar for the reason that they radiate from isolated peaks which rise far above the neighboring mountains. These peaks are all of volcanic origin, and lingering manifestations of internal heat are to be seen in the hot springs and fumaroles in their craters. Far down their flanks, and in some instances for miles out on the surrounding plains, there are moraines and other evidences showing that in Pleistocene times the climatic changes, which caused half of the continent to be mantled in ice, were there in operation also, and gave origin to glaciers of the same general character as those still existing, but of far greater extent.

CHAPTER V.

GLACIERS OF CANADA.

THE Cordilleras pass northward from the United States and traverse the western part of Canada. As already stated, the general mountain system subdivides northward and is composed of several series that are distinct and separate both topographically and geologically. The northern part of the system is far from being completely explored, but many rugged peaks are known to reach the limit of perennial snow, and to be covered in part with glaciers. About the only mountaineering that has been done in Canada has been in the Selkirk and neighboring ranges, recently made accessible by the building of the Canadian Pacific railroad. When explorers have conquered other mountains, there is reason to believe from the reports of hunters, prospectors, and others, that our knowledge of the ice fields will be greatly extended, and that many fine examples of glaciers, of the alpine type, will be found clustering around the higher summits.

The glaciers of the Selkirk mountains are known principally from explorations made by Rev. W. S. Green, in 1888. At least one example, the Illecellewaet glacier, is in sight from Glacier house on the Canadian Pacific railroad, and has attracted the attention of thousands of travelers from car windows. Views of this easily accessible glacier are given on Pls. 11, 12. The scenery of the Selkirks, as seen from near the summit of a rugged peak called Mount Sir Donald, near Glacier house, is described by Green as follows: [1]

"We were on a pinnacle of rock, according to the barometer, just 10,000 feet above the sea. On all sides were vast precipices, and down these precipices our eyes ranged to the green, forest-clad valley of Beaver creek, the river being visible for many miles, winding, with an infinity of curves, 6000 feet below us.

"Beyond the river rose a range of hills with flattish plateaus on the top, flecked with snow. Still farther to the eastward, range rose upon range, fading into purple and blue. Above them all the Rockies, bearing silvery white glaciers, formed a sharply defined sky line, and were visible

[1] "Among the Selkirk Glaciers" (Macmillan & Co., London, 1890), pp. 86, 87.

for over 150 miles. This wonderful panorama constituted our view to the eastward. To the southward it was totally different; in that direction the undulating fields of glaciers lay like a great soft white blanket covering up everything for ten miles, beyond which other snow-seamed crags rose, rivaling, probably in some cases surpassing, Sir Donald in elevation. To the westward other ranges were to be seen, and one high ridge of black precipices capped by ice rose high above the glacier and seemed to dominate the scene. . . . Beyond the valley of the Illecellewaet to the northwest, some fine peaks were visible; one dark, bare rock pinnacle bearing northwest was most striking, and, no doubt, over 10,000 feet high. Our view to the northward was blocked by the last great crags of Sir Donald, from which we were cut off by a notch 200 feet deep. At its bottom a narrow rock *arête* joined the precipice below us with the face of the final peak. Below this *arête*, on one side, lay the glacier visible from Glacier house (the Illecellewaet glacier); and on the eastern side, in a deep hollow, a fine glacier which we named the Sir Donald glacier commences its course, and flows outward in beautiful fan-like structure, in the direction of Beaver creek."

During the explorations carried on by Greene, the Illecellewaet glacier was traversed to near its source, and several secondary glaciers discovered. A sketch map of 500 square miles, embracing many rugged peaks and a score of small névé fields and glaciers, was constructed, and many photographs taken. With this excellent beginning it is hoped that others as well qualified for mountaineering as the distinguished writer just quoted will seek for new wonders among the magnificent mountains of Canada.

The present writer visited the Illecellewaet glacier in the spring of 1891, and saw something of the wonders of the Selkirks. My visit, although brief, served to confirm the enthusiastic descriptions of that remarkable region given by many travelers. The glaciers about the higher peaks, descending, in some instances, into the deep-green coniferous forests, and producing striking contrasts of color, are of the same general character as the glaciers of the High Sierra and the Cascade mountains. The extent of true glacial ice is greater than is presented by the ice bodies of California, and the shining snow fields from which it flows are broader than the similar areas on the mountains of Oregon and Washington. In comparison with the glaciers of Central Europe, the Selkirk glaciers lack the strongly defined, stream-like character of the Mer de Glace, or the Gorner glacier, for example, and, in general, do not

FIG. A.—ILLECELLEWAET GLACIER, CANADA.

(Photograph by Wm. Notman & Son.)

FIG. B.—ILLECELLEWAET GLACIER, CANADA.

(Photograph by Wm. Notman & Son.)

display the distinctive features of alpine glaciers so well as the archetypes of that class of ice bodies.

Glaciers occur farther north in Canada on the various divisions of the Cordilleras, more especially in the region drained by the Stikine, and to the northeast of Mount St. Elias ; but these are so closely associated with the vast ice bodies of Alaska, that in the present sketch political boundaries will be ignored and all of the glaciers of the far Northwest included in a single chapter.

CHAPTER VI.

GLACIERS OF ALASKA.

In purchasing Alaska the United States not only acquired a vast territory rich in natural resources, but added new wonders to her already varied scenery. As shown on the preceding pages, the glaciers of the United States, previous to the purchase of Alaska, were by no means insignificant, although at that time almost unheard of, and even now but imperfectly explored. When we include Alaska and the adjacent portion of Canada, the field for glacial study becomes almost unlimited.

The glaciers of the Alaskan region are of the alpine and piedmont types. Masses of buried ice and frozen subsoil in the tundra region bordering Bering sea and the Arctic ocean and along arms of the great rivers are not here included, and will be described in advance. All of the true glaciers are confined to the southern portion of the territory and depend on favorable combinations of climatic and topographical conditions for their extent and geographical distribution. The mountains of the Alaskan region occur mostly along its southern border, adjacent to the Pacific ocean, and attain their greatest elevation near the 141st meridian. The culminating peak, so far as at present known, is Mount Logan, 19,500 feet high. Second in rank stands Mount St. Elias, 18,023 feet in elevation. These and a host of sister peaks rise from a vast névé region having a general elevation of 8000 or 9000 feet. The entire Pacific border of Alaska is rugged and mountainous, and presents some of the most sublime coast scenery to be found in the world. The currents of the ocean bring warm water to the very base of these lofty mountains, thus furnishing an evaporating surface in close proximity to cold peaks where the vapors are condensed. About Mount St. Elias, as shown by two seasons spent by the writer in exploring that region, the winds from the south are warm and moist, and are almost invariably accompanied by clouds and snowstorms on the mountains. The north winds are dry, and are especially welcome, as they are frequently accompanied by clear skies and brilliant sunshine. The conditions, taken all together, are remarkably favorable for the growth of glaciers.

Narratives of Early Voyagers. — The early voyagers to the southern shore of Alaska saw many bodies of ice, some of which we now know are extensive glaciers. Sir Edward Belcher, in his account of the voyage of the *Sulphur*, makes brief mention of cliffs of ice on the borders of Icy bay, near the the foot of Mount St. Elias.

In the account of Vancouver's voyages, bodies of ice, terminating in cliffs at the water's edge, are mentioned as being numerous on the borders of Prince William sound. In the same narrative brief descriptions are given of an accumulation of ice in an arm of Stephen's passage, northwest of Sitka, and also among the mountains along the coast opposite Admiralty island. Two large bays opening north and west from Point Couverdeen are described as terminating in solid mountains of ice rising perpendicularly from the water's edge. Beyond the brief statement of the presence of large masses of ice at sea level, the narratives of the bold explorers who first sailed along the wild Alaskan coast are of little interest to the special student of glacial phenomena.

Some of the glaciers along the northern bank of Stikine river were visited by Professor William P. Blake[1] in 1863. These ice bodies are of the alpine type, and descend nearly to the level of the river. A popular account of the remarkable scenery of the Stikine river, in which glaciers play a conspicuous part, was given by W. H. Bell, together with greatly exaggerated illustrations, in Scribner's Monthly for April, 1879.

The positions of many glaciers to be seen from the decks of passing vessels between the mouth of Stikine river and Cook's inlet, a distance of about 1000 miles, have been indicated from time to time on the charts published by the U. S. Coast and Geodetic Survey. Brief accounts of the fine glaciers of Glacier bay were published by G. W. Lamplugh, in Nature,[2] in 1886, but did not serve to make the wonders of that region generally known. Among the earlier accounts of the glaciers of Alaska, the most noteworthy are those from the pen of Dr. W. H. Dall, the pioneer explorer of the Yukon river and the author of a justly celebrated work on "Alaska and its Resources."

This brief account of the sources of information relating to the glaciers of the Alaskan region available in 1883, when the author's sketch of the "Glaciers of the United States" was written, brings us to the time

[1] Blake's observations were the earliest made in southeastern Alaska that have much scientific value, and were recorded in the American Journal of Science, vol. 44, 1867, pp. 99–101. Republished with a map, in a report to the Secretary of State, bearing the title, "Geographical Notes upon Russian America and the Stickeen River. Washington, 1868."

[2] Vol. 33, pp. 299–301.

when a wide interest was awakened in the natural features of the "Far Northwest."

Recent Explorations. — Of the more recent Alaskan explorers we are indebted especially to John Muir, who discovered the magnificent glacier since named in his honor, as well as many others that come down to the sea, or may be seen from a canoe while threading the intricate straits and bays of the southeastern portion of the territory. More recently the glaciers of Glacier bay have been studied by Professor G. Frederick Wright and Professor H. Fielding Reid, and the still vaster ice streams in the regions about Mount St. Elias and Disenchantment bay have been visited and described by a number of persons. Reference to the principal contributions to the literature that has grown out of these explorations are given in the following footnote.[1]

Some of the glaciers flowing northward from the mountains of southern Alaska were examined and their positions mapped by Dr. C. Willard Hayes, of the U. S. Geological Survey, during a bold and highly successful exploration from the Yukon to Copper river, in company with Lieutenant Frederick Schwatka, in 1891.[2] Other northward-flowing glaciers were observed by E. J. Glave in 1891 and 1892, to the northwest of the head of Lynn canal.

In addition to the writings of the travelers referred to above, much

[1] John Muir, "Alaska," in Am. Geol., vol. 11, 1893, pp. 287–299.

G. F. Wright, "The Ice Age in North America," Appleton & Co., 1889.

H. Fielding Reid, "Studies of Muir Glacier," in National Geographic Magazine (Washington, D.C.), vol. 4, 1892, pp. 19–84.

Frederick Schwatka, "The Expedition of the New York Times," in Century Magazine, April, 1891.

William Libbey, Jr., "Some of the Geographic Features of Southeastern Alaska," in Am. Geog. Soc., Bull., 1886, pp. 279–300.

H. W. Seton-Karr, "Shores and Alps of Alaska," London, 1887.

H. W. Seton-Karr, "Alpine Regions of Alaska," in Roy. Geog. Soc., Proc. (London), vol. 9, pp. 269–285.

William Williams, "Climbing Mount St. Elias," in Scribner's Magazine, vol. 5, 1889, pp. 387–403.

H. W. Topham, "An Expedition to Mount St. Elias," in the Alpine Journal (London), vol. 14, 1889, pp. 345–371.

I. C. Russell, "An Expedition to Mount St. Elias" (1890), in National Geographic Magazine (Washington, D.C.), vol. 3, 1891, pp. 53–203.

I. C. Russell, "Second Expedition to Mount St. Elias," 1891, in 13th Ann. Rep. U. S. Geol. Surv., pp. 1–91.

John Muir, Century Magazine, vol. 50, 1895, pp. 234–247.

[2] "An Expedition to the Yukon District," in National Geographic Magazine (Washington, D.C.), vol. 4, 1892, pp. 117–162.

popular interest in the subject here treated has been awakened by the enthusiastic narratives of tourists who have made trips on the excursion steamers sailing from Puget sound through the celebrated "inland passage" to Taku inlet, Lynn canal, Glacier bay, etc.

From this brief summary it will be seen that the literature relating to the glaciers of the Alaskan region is already voluminous. Instead of attempting to give a detailed account of all the glaciers that have been described, a few of the best-known examples will be selected as types. These may be taken as representatives of the many hundred already known, and as indicating the principal features of the probably still greater number that have only been seen from a distance or remain to be discovered.

Tide-water Glaciers.

It is convenient to give a special name to glaciers which enter the ocean and break off so as to form bergs. One should bear in mind, however, that the ice streams or ice sheets which terminate in this manner do not differ from neighboring glaciers that fail to reach the sea, except in the fact that they actually meet tide-water. But the striking appearance of their broken extremities rising in sheer precipices above the surf that beats against their bases, renders them especially noteworthy and warrants their having a special designation.

The tide-water glaciers of Alaska are the ones that claim the greatest share of admiration from tourists on account of the wonderful coloring and marvelous beauty of their ice cliffs and the picturesqueness of the floating islands of ice to which they give origin. The approach to a tide-water glacier is usually first made known by the fleet of bergs that dot the water and chill the atmosphere. These become more numerous as one proceeds, and many times completely cover the water before the ice cliffs from which they came can be seen. Indeed, at times, the floating bergs form an impenetrable pack through which it is impossible for a vessel to advance. The vicinity of a glacier which terminates in the sea is frequently made manifest also by the roar of avalanches, as fresh masses of ice fall from its face and join the fleet of gleaming bergs crowding the adjacent waters. The noise of the falling fragments may be heard many miles, and sounds like distant thunder or the discharge of heavy guns.

When a large tide-water glacier is seen for the first time, the beholder is fascinated by its beauty, especially if it is illuminated by a brilliant sun, and learns a new lesson, for the reason that the scene is so different

from the popular idea of the appearance of glaciers, derived principally from the well-known ice streams of Switzerland.

In going to Alaska by the customary "inland passage," through the picturesque archipelago fringing the coast from Puget sound northward, the first floating ice is usually seen soon after passing through Wrangell narrows and emerging into an arm of Frederick sound. These bergs come from a small glacier long known to the Indians as Hutli, or the thunderer, on account of the noise produced by ice falling from its face.[1] The glacier is hidden by the bold, forest-covered shores of Hutli inlet, and is not seen by travelers along the course ordinarily followed by vessels.

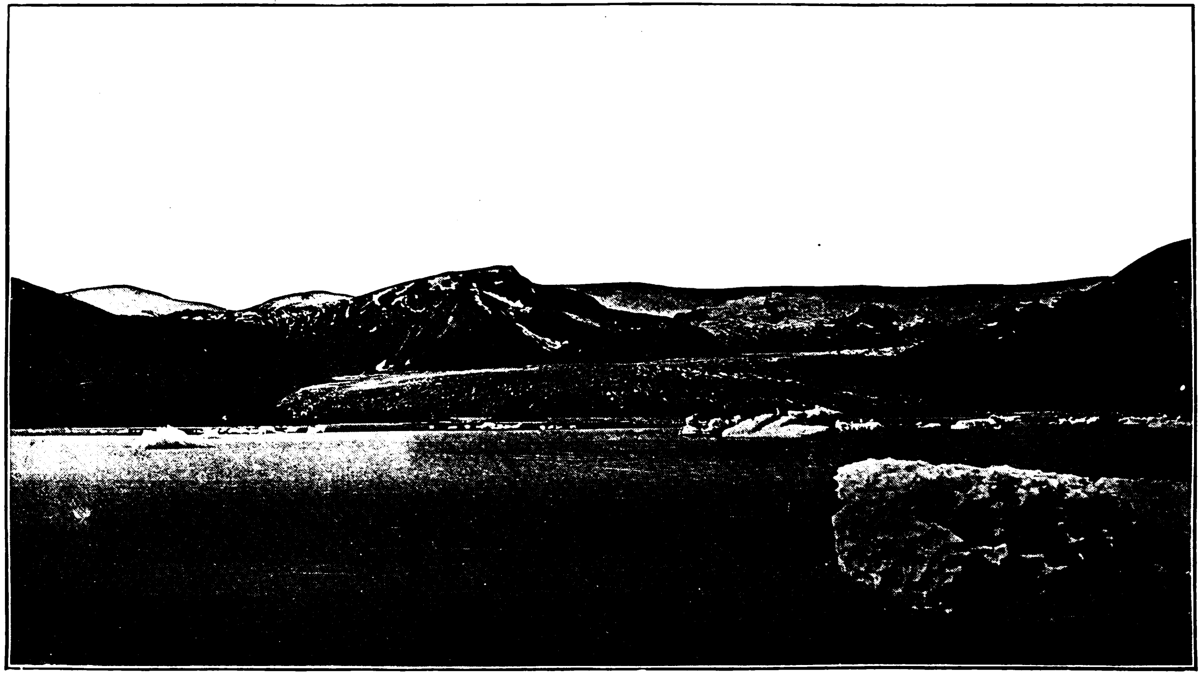
Proceeding northward, glimpses are obtained here and there on the mountains of the mainland, of gleaming snow fields and of the blue of glacial ice, rising above the nearly universal green of the forest-covered shores. The first unobstructed view of a large glacier is not had, however, until one enters a wild fiord known as Taku inlet. On the northwest shore of this indentation of the coast, and seen on the left as one enters it from the sea, a stream of ice descends from the mountains and expands into a broad, fan-like terminus at the margin of the water. This is the Norris glacier shown on Plate 11. The mud and sand brought out by the streams issuing from the ice have formed a fringe about its terminus, so that it is now separated from the water of the inlet by a barren plain of sand and mud crossed by many bifurcating streams.

Taku Glacier.

The comparative mildness of the scenery at the Norris glacier does not prepare one for the marvels that await him a few miles beyond. At the head of Taku inlet, and filling the gorge from side to side so as to hold the waters of the ocean in check, is a wall of ice formed by the extremity of a typical tide-water glacier. This is the Taku glacier, as it has long been called by both Indians and white people. Unfortunately an attempt has recently been made by the U. S. Coast and Geodetic Survey[2] to supplant this name by another less appropriate.

[1] This glacier was first seen by John Muir, and the Indian name which he accepted should be recognized. See American Geologist, vol. 2, p. 291.

[2] The Hutli and Norris glaciers referred to above, as well as several others in south-eastern Alaska, have also suffered a recent change of name on the charts of the U. S. Coast and Geodetic Survey. I wish to protest against this useless duplication, especially when the names of persons temporarily in political power, and for this reason simply, are put in place of names long in use, and especially of pronounceable Indian names.



NORRIS GLACIER, TAKU INLET, ALASKA.

(After G. F. Wright.)

Taku glacier heads far back in the mountains, no one knows where, and flows toward the coast as a well-defined ice stream. It is yet in its full strength when it reaches an arm of the sea and enters on an unequal struggle with the waves. The wall of ice rising above the water is by estimate 200 feet high, and nearly a mile in length. Its face is not one sheer precipice, but is broken into buttresses and columns and diversified by alcoves and recesses. Its crest line is irregular and serrate, and surmounted by spires and battlements of the most varied description. The details of the craggy slope are constantly changing and are never the same for two successive days. In fact, marked changes occur from hour to hour as fresh masses fall into the sea. The rapid waste, manifest especially on summer days, is counterbalanced by the resistless onward flow of the ice, so that but slight changes in the position of the terminus can be recognized from year to year. Like many glaciers in the same region its extremity is probably slowly retreating, however, but no measurements have been made to show the rate of recession.

The color of the fractured and cleft ice cliffs is as varied and beautiful as their ever-changing forms. The surfaces that have been longest exposed to the atmosphere are white and glittering, on account of the multitude of vesicles formed in the partially melted ice ; but the clefts and caverns reveal the intense blue of the crystal mass within. In the deeper recesses the light issuing from the interior is of the darkest ultramarine, so deep that it appears almost black in contrast with the brilliant outer surface. In the full glory of an unclouded summer day the scene becomes resplendent with the reflected glories of the sea and sky. The ice cliffs blaze and flash in the sunlight until one can scarcely believe that it is an everyday, earthly scene that meets his admiring gaze. The observer to whom such wonders are novel may well fancy that the picture before him is but the fantasy of a dream. One is awakened from such reverie, however, by a crash like the roar of artillery, when an avalanche falls from the cliffs of light and is engulfed in the turbid waters below. The white foam shot upwards by the avalanche, rises high on the icy precipice, and perhaps dislodges other tottering pinnacles, which reawaken the echoes in the neighboring mountains. After each crash, crested waves, starting away from the scene of commotion, set numerous bergs rocking, and break in lines of foam on the adjacent shore. Floating ice frequently whitens the entire surface of Taku inlet, and is occasionally carried by the wayward currents far out into Stevens' passage and up Gastineau channel to beyond the town of Juneau.

In former years Taku glacier extended far south of its present terminus and received Norris glacier as a tributary. The former height of the ice is clearly marked by the smoothed and rounded surfaces of the cliffs, and by grooves and striations, for about 2000 feet above the water, on the precipitous mountains enclosing the inlet. Above that height the rough and angular sculpturing due to frost, rain, and rills is in marked contrast to the ice-worn surfaces below. The glacier is still receding, and in a decade or two will probably have shrunken so that it will no longer reach the inlet, but will end as Norris glacier now does, with a low frontal slope. The waters from the glacier will then build an alluvial plain about its extremity, and it will acquire the subdued and unpicturesque features characteristic of dying alpine glaciers.

Muir Glacier.

(A map of Muir glacier is given on Plate 12.)

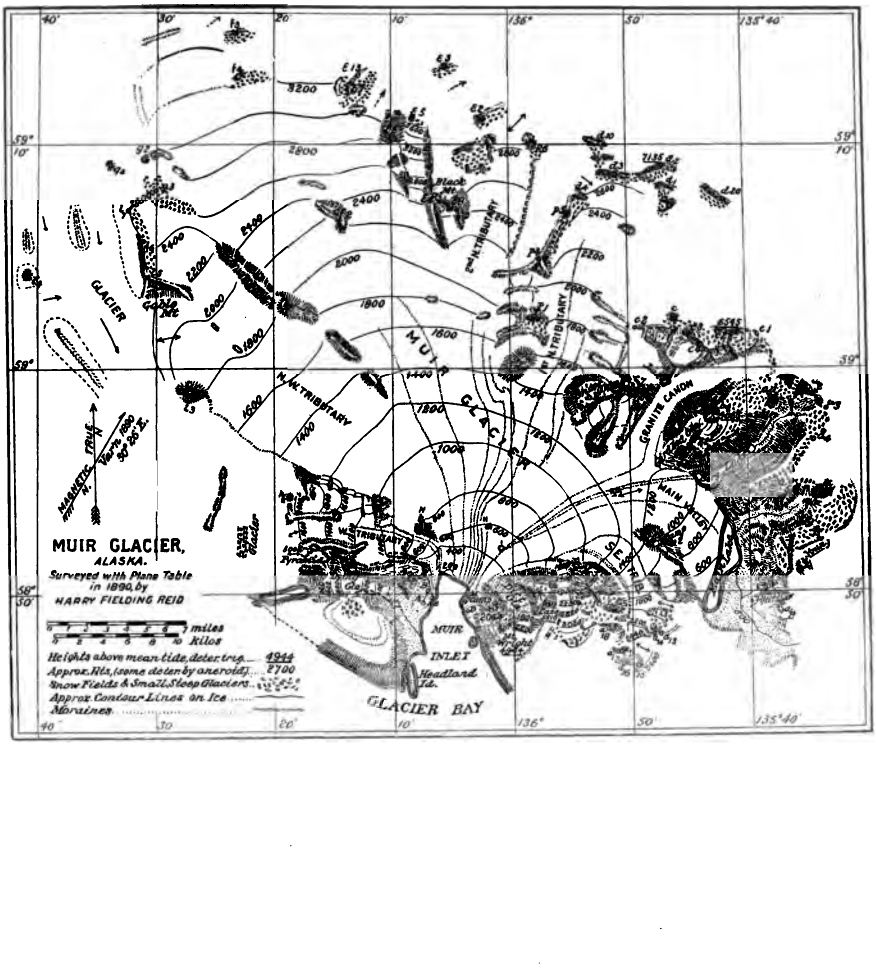
Proceeding westward from Taku inlet, the next tide-water glacier is met with in Glacier bay. Several glaciers there pour their icy floods into a land-locked arm of the sea. The wonders of this splendid bay, now familiar to thousands of tourists, were unknown to civilized people fifteen years ago. The bay and the magnificent glacier on its shores were discovered by John Muir, the intrepid mountain climber and poetic writer of California, in 1878. His account of the pioneer trip to *Sita-da-ka*, as the bay was called by his Indian companions, has recently been published, and is a most graphic and interesting account of a canoe trip among the islands of southeastern Alaska.[1]

One of the largest and at present the best-known glacier entering Glacier bay has been named Muir glacier, in honor of its discoverer. In 1886, Prof. G. Frederick Wright, with three companions, encamped for about a month near the eastern end of the ice cliffs in which it terminates, and began the study of its general features, its motions, the formation of icebergs, etc.[2]

The observations begun by Wright were continued and greatly

[1] This brief account of explorations in southeastern Alaska was first published as a "folder" by the Northern Pacific Railroad Co. and afterward printed in the American Geologist, vol. 11, 1893, pp. 287–299. A revision of this charming paper, accompanied by fine illustrations, appeared in Century Magazine, vol. 50, 1895, pp. 234–247.

[2] The principal account of these observations may be found in Wright's book, "The Ice Age in North America," Appleton & Co., 1889.


MUIR GLACIER,
ALASKA.
Surveyed with Plane Table
in 1890, by
HARRY FIELDING REID
miles
Kilos
Heights above mean tide, deter. trig. 4944
Approx. Hts, (some deter. by aneroid) 2700
Snow Fields & Small, Steep Glaciers ....
Approx. Contour Lines on Ice ......
Moraines ......
MAGNETIC N.
TRUE N.
Var. 1890 30° 26' E.
GLACIER
MUIR GLACIER
N.W. TRIBUTARY
GRANITE CAÑON
MAIN VALLEY
MUIR INLET
Headland Id.
GLACIER BAY

extended by Prof. H. Fielding Reid, and a number of assistants, in 1890,[1] and again in 1892.

The present writer visited Muir glacier in 1890, as a passenger on the excursion steamer *Queen*, and spent a few hours in viewing the general features of the region. Nearly all of the facts presented below in reference to the more detailed characteristics of the glacier, however, are taken from the reports of Professors Wright and Reid.

On entering Glacier bay from Icy strait, one sees before him a magnificent inlet, the head of which is beyond the reach of vision. The bay is 35 miles long and from six to ten miles broad. To the west rises a group of snow-clad and glacier-scored mountains, culminating in Mt. Fairweather, over 15,000 feet high. The ice flowing from the northeast slope of this rugged elevation reaches the western shore of Glacier bay and forms a series of splendid tide-water glaciers. These were explored and mapped by Reid in 1892, but an account of them has not yet been published, although their names and positions are sometimes roughly indicated on charts of the bay.

As one proceeds up the Glacier bay large fields of floating ice are usually encountered and numerous bergs are always in sight. These floating fragments of glacial ice are driven here and there by the winds and currents, so that the details of the arctic picture are constantly changing. At times, the ice is packed in such a way that it is difficult if not impossible for vessels to force a passage through it so as to gain the immediate vicinity of the glacier beyond.

The truly wonderful scenery of Glacier bay appeals most forcibly to the imagination during the lengthened twilights of summer. The latitude corresponds with that of the extreme north of Scotland. In summer the sun declines but a few degrees below the northern horizon and the nights are sufficiently light to reveal the white-robed mountains in half-tones of the most delicate beauty. At such times the thousands of bergs and the broad ice-floes are transformed by the tricks of the mirage into shapes of the most remarkable description. Vast cities, with colonades and ruined temples, towers and battlements, appear with marvelous realism where only a few moments before there was but a glassy plain of water studded with fragments of floating ice. Sheaf-like fountains and monumental shafts appear with such faithful imagery that one is more than half inclined to yield to the delusion and believe that the

[1] A report on this survey was published by Reid in the National Geographic Magazine, vol. 4, 1892, pp. 19–48.

apparitions are real. The weird beauty of the expanse of ice-freighted waters and the cold, stern, snow-covered mountains, as well as the lively anticipation of what is to come, make a sail on those northern waters, in brilliant weather, an event that thrills the fancy and leaves an indelible picture on the memory.

On nearing the head of Glacier bay and approaching Muir inlet, one beholds a palisade of ice nearly two miles long and from 130 to 210 feet high, rising from the water and uniting mountain with mountain and forming a wall across the head of the inlet so as to hold back the waters of the ocean. This wall of ice, shown on Plate 3, is the extremity of the justly famed Muir glacier. As one draws near, the surface of the glacier can be seen above and beyond the line of precipices in which it terminates. The eye follows the gradually ascending plain of white to the distant mountains, where it divides into many branches, separated by wild, rugged peaks that stand as islands in the vast snow field.

Soundings made in the central portion of the inlet as near to the ice front as vessels can safely venture, by estimate a thousand yards from the base of the cliffs, gave a depth of 720 feet. The glacier extended south of its present limit a few years since and occupied the site where this sounding was taken, and was then certainly fully one thousand feet thick. There are reasons for believing that recent changes have not sensibly altered the depth of the ice.

Surveys made by Reid have shown that the onward flow of the ice near the end of the glacier, in its central portion, is seven feet per day, and decreases to zero at the sides.[1] Knowing the width and thickness of the ice and its rate of flow, it has been computed that about thirty million cubic feet of ice break away each summer day and join the fleet of bergs that whiten the adjacent waters. The flow of the ice in winter is less than in summer, but no winter measurements have been made. Judging from the behavior of other glaciers, it seems safe to assume that the annual onward flow where the current is strongest is not less than 2000 feet.

The color of the ice wall in which the Muir glacier terminates is of the same marvelous character as already noted at Taku glacier. It is especially remarkable for the deep ultramarine of the recesses. The multitude of pinnacles and spires forming the serrate crest, as well as each outstanding buttress of the mighty wall, are brilliant white. The

[1] S. Prentiss Baldwin, " Recent Changes in Muir Glacier," in American Geologist, vol. 11, pp. 367–375.

contrast in color and in form are greatest and most beautiful when the side lights of morning and evening bring out the details in strong relief. The crumbling cliffs are a ruin that is constantly renewed. The resistance offered by individual features to the sun and air is brief, but new forms take the place of those that succumb, and the general effect remains the same. One never wearies of watching the ever-changing picture presented by the long line of cliffs in varying lights, or of studying the formation of bergs as buttress after buttress gives way to the attacks of the waves and topples over into the sea.

Icebergs. — The avalanches from the faces of tide-water glaciers take place without warning and are frequently startling. The roar of the falling masses on hot summer days is sometimes almost continuous.

FIG. 5. — ICEBERG, MUIR INLET, ALASKA.

Muir states that in the case of the glacier named in his honor, for twelve consecutive hours the number of discharges loud enough to be heard a mile or two were, by actual count, one in five or six minutes. The dislodged masses falling into the sea cause great disturbances, and send the white foam surging high up on the cliffs. On one occasion, while traversing the surface of Muir glacier near its extremity, my attention was attracted to a pinnacle higher than its neighbors, on the brink of the precipice overlooking the water. While I was still gazing, it suddenly disappeared from sight, and after a few seconds a cloud of spray rose in its place. This is the only instance I recall in which the spray dashed upward by falling ice rose higher than the general level of the crest of the precipice from which it was detached.

The icebergs of Glacier bay and other portions of the Alaskan coast are small in comparison with those of the Greenland waters. Actual measurements are not at hand; but after several canoe trips among the floating ice, I should judge that the larger bergs are frequently 150 to 200 feet long by 50 to 100 feet broad, and rise 20 to 30 feet above the water. As they float with about one-seventh of their mass exposed, their total depth can be readily estimated.

In sailing up Muir inlet or any other arm of the sea on the wild Alaskan shore where tide-water glaciers discharge, one notices that the bergs vary in character, but may be grouped in three quite well-defined classes. Some are of dazzling whiteness; others are of the color of turquoise or beryl; others, again, are dark with dirt and stones. On watching the ice cliffs where these children of the glaciers are born, we find that when pinnacles already whitened by exposure to the air fall into the sea, they float away as white bergs. If we watch them drifting over the still water and appearing in the distance like a fleet of gleaming sails, we note that occasionally a white berg suddenly turns over with great commotion and joins the fleet having blue for their banner. The reason for the change in color is that previous to turning over the porous exterior of the submerged portion of the berg was dissolved away so as to expose the compact ice of the interior. The sudden reversion of position is due to unequal melting, which changes the center of gravity of the mass. A cone of ice in which the height is about equal to the diameter of the base, will float with its apex down. When a berg approaches a conical form, the position of greatest stability is one in which the side having the larger mass is uppermost. Bergs do not become *top-heavy* and turn over, as is sometimes stated, but become *bottom-buoyant* and tend to adjust themselves to the medium in which they float.

Blue bergs are also formed by the breaking away of portions of the submerged ice foot of tide-water glaciers. These are frequently of large size, and rise from below the surface of the water well in advance of the visible end of the glacier. Their emergence is sudden. They bound to the surface, and rising well above it carry tons of water with them. After rocking to and fro for several minutes as if to be sure of their freedom after centuries of imprisonment, they quiet down and float slowly away as shimmering islands of the most exquisite blue. The precise manner in which the bottom ice of a tide-water glacier breaks off is not definitely known. Reid has made observations in this connection at Muir glacier, and has been led to think that the upper portion of the submerged ice foot extends

FIG. A.—ICE CLIFF AT THE END OF MUIR GLACIER, ALASKA.

(Photograph by H. F. Reid.)

FIG B.—ICE CLIFF OF MUIR GLACIER AT LOW TIDE.

(Photograph by H. F. Reid.)

beyond and overhangs the lower portion, for the reason that the flow of a glacier is greater at the top than at the bottom, and also because the melting of the submerged ice, at least near the surface of the sea, is in excess of the melting of the portion above water. These considerations have led to the assumption that a longitudinal section of the extremity of a glacier terminating in deep water would present the features indicated in the following diagram:

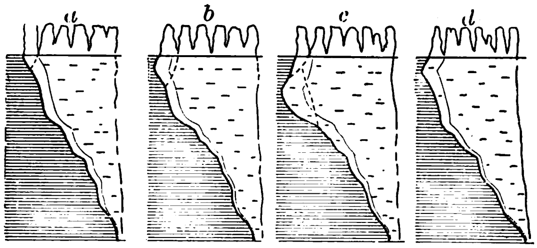


FIG. 6.—IDEAL SECTION OF THE END OF A TIDE-WATER GLACIER. AFTER REID.

The broken lines extending down from the surface and curving outward are thought to represent the direction taken by fractures, which permit portions of the extremity to break off and leave an overhanging mass near the summit of the cliff. The submerged portion would then break away, and owing to its irregular form, might be thrown outward as it rose, so as to come to the surface some distance from the visible base of the ice cliff.

The principal objection to this explanation, so far as can be judged from the observations available, is that the bergs rising from below reach the surface too far out from the ice cliffs. In some instances observed by the present writer, they came to the surface not less than a thousand feet from the visible ice foot. Besides, the observed rapid melting of the submerged ice pertains to the portion within a few feet of the surface. Near Muir glacier the surface temperature of the water of Muir inlet, as observed by Prof. Wright, was 40° F. This would insure rapid melting, but what the temperature is below the surface no one knows.

Another explanation of the formation of bergs from the submerged portion of a glacier, is that the falling of avalanches from the visible portion of the ice cliff is greater than the melting of the submerged portion. A terrace-like projection of the deeply submerged ice foot is then produced, and portions of the protruding base break away from time to time, owing to their buoyancy, and rise to the surface. The conditions here postulated are illustrated in the diagram on the following page.

Reid objects to the hypothesis just stated, and suggests that the height to which the suddenly emerging bergs rise above the surface of the water is not so great as should be expected if they came from a depth of several hundred feet. Until observations or computations have shown that this objection is valid, however, it can have but little weight. Which of these two explanations is correct, or what portion of each may be accepted with confidence, must be determined by future observations. It would not be difficult, or especially dangerous, to make soundings and temperature observations in the central part of Muir inlet close to the visible base of the ice wall, and thus ascertain the slope of the submerged portion of the glacier, and also to what depth the warm surface temperature extends.

The black, dirt-covered bergs occasionally seen in the vicinity of tide-water glaciers are fragments of the bottom layer of ice, or perhaps more frequently portions of the sides of crevasses in which stones and dirt had

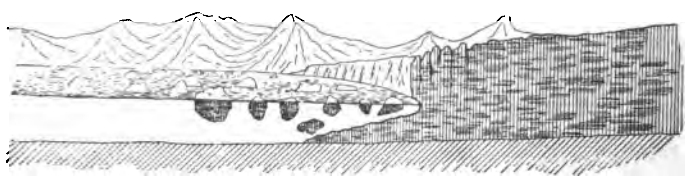


FIG. 7. — IDEAL SECTION OF THE END OF A TIDE-WATER GLACIER.

lodged. These bergs, bearing a freight of foreign material, derive their principal interest from the fact that they carry their loads to localities more or less remote from their place of origin, and may drop them where fine water-borne sediments are accumulating.

An Ancient Forest Buried beneath the Ice. — When the excursion steamer to Glacier bay reaches within about a mile of Muir glacier, the anchor is dropped and passengers are given an opportunity to go ashore.

On landing on either side of the inlet, the first fact that attracts the attention of the geologist is the presence of a heavy deposit of cross-stratified sand and gravel below the extremity of the glacier. This gravel deposit passes beneath the glacier and is plainly of more ancient date than the advance of the ice over it. In this deposit there are many trunks and branches of trees; and on the west side of the inlet there are a score or more trunks of spruce trees, still standing as they grew, which have been exposed by the removal of the strata in which they were formerly buried. A photograph of this ancient forest is presented in Fig. B, Plate 14. The history of this deposit of sand and gravel and of the

forest entombed in it is in brief as follows: The glacier was formerly not so extensive as now, having undergone a retreat after a preceding period of marked extension, and a dense forest grew at least on the sides, if not in the center, of the valley left exposed below its terminus. Coincident with the retreat of the glacier and the growth of the forest there must have been an elevation of the land which excluded the water from a portion of the inlet now submerged. While the forest was still standing, the streams from the glacier, then terminating in the valley to the north, brought down large quantities of gravel and sand and built up an alluvial cone about the extremity of the ice. As this alluvial cone, which probably ended in the sea and in fact was in part a delta, increased in size, it invaded the adjacent forest and buried the still upright trees. A subsequent advance of the glacier caused the ice to override the gravel with its entombed forest. When the glacier once more retreated the deposits were uncovered and cut away by streams flowing from the ice, so as to expose the trees buried within their mass. This last step in the history of the inlet is still unfinished. The terminus of the glacier is still receding, and as the streams flowing from it are still excavating channels through the gravel, it is to be expected that additional portions of the buried forest will be uncovered. In the moraines far up on the surface of the glacier and on the islands of rock that project above its surface, there are bleached and water-soaked branches and trunks of trees, which show that the now desolate mountains bordering the ice were formerly more or less forest-covered.

The process by which forests about the extremities of glaciers became buried in alluvial cones may be observed at Norris glacier and about the expanded extremity of Davidson glacier, but is illustrated in a far more striking manner along the borders of Malaspina glacier, to be described on a subsequent page.[1]

Characteristics of the Glacier's Surface. — At the locality on the east side of Muir inlet, where excursionists usually land, the subglacial gravels described above are well exposed. The border of the glacier and the character of the ice at the extremity where it overhangs the sea may

[1] The literature bearing on the gravel deposits and buried forests at Muir glacier may be found as follows: G. Frederick Wright, "Ice Age in North America," pp. 58-63, also in American Geologist, vol. 8, pp. 330, 331. H. P. Cushing, American Geologist, vol. 8, pp. 207. I. C. Russell, American Geologist, vol. 9, pp. 190-197. H. Fielding Reid, National Geographic Magazine, vol. 4, pp. 38, 40, pl. 12. I. C. Russell, "The Influence of Débris on the Flow of Glaciers," Jour. Geol., vol. 3, 1895, pp. 823-832.

also be examined, and the broad surface of the ice that fills the valley easily reached. After walking over the surface of the ice between long lines of moraines, where it is as level and smooth as a well-kept pavement, one may climb a rocky promontory on the side of Mt. Wright, and obtain a wide-reaching view of the remarkable scene that lies spread out before him. There is not a tree or shrub in sight, but the crevices between the rocks are bright with alpine flowers. The many streams of snow-covered ice that unite to form the main trunk glacier may be distinctly traced for a score or more of miles to their sources in the deep valleys and amphitheatres in the surrounding mountains. With the aid of the map

FIG. 8.—SIDE VIEW OF A MEDIAL MORAINE, MUIR GLACIER. PHOTOGRAPH BY H. B. LOOMIS.

published by Prof. Reid, reproduced on a reduced scale on Plate 12, one can obtain a most graphic idea of the entire system of ice drainage terminating in Muir inlet. The area of the actual ice surface in view is about 350 square miles. The total area from which the ice drainage is derived is not far from 800 square miles.

Looking down on the glacier from an elevated station, for the first time, one is filled with awe and wonder at the vastness of the panorama so clearly and distinctly visible. The rough broken ice with shining pinnacles overlooking blue crevasses, in the central portion of the stream, just before it makes its final plunge into the sea, reveals the line of greatest movement. It was in this all but impossible portion of the glacier that Prof. Reid after great exertion placed his signals in 1891, and measured

FIG. A.—SURFACE OF MUIR GLACIER; WITH WHITE GLACIER, A TRIBUTARY.

(Photograph by H. F. Reid.)

FIG. B.—BURIED FOREST AND GRAVEL DEPOSITS AT END OF MUIR GLACIER.

(Photograph by H. F. Reid.)

the strength of the glacial current. The actual center of the glacier was not reached, however, as the ice was there so shattered as to be impassable.

The number of narrow dirt-covered ridges running parallel with the border of the glacier, and extending from the summits of the cliffs overhanging the sea, up the surface until they disappear beneath the névé snow of the higher regions, or reach rocky islands in the glacier from which they originate, mark the border of the individual ice streams composing the main and highly compound central trunk in which all of the tributaries unite. We note, also, that the long, narrow moraine belts stand in relief above the general surface like railroad embankments. In reality these huge piles of stones and earth, as they appear, are but a thin sheathing, covering ridges of ice which they have preserved from melting while the general surface wasted away.

Fully a score of secondary glaciers are in sight from the elevated station on which the reader is supposed to stand, but there are still other tributaries to the eastward that are concealed from view by Mt. Wright and neighboring elevations.

With the accompanying map in hand, one may readily identify the various features of the vast landscape. One evident fact is that the ice fills the valleys to a depth of many hundred feet, leaving the steep mountain sides above the established grade almost free of snow.

The medial moraines coming from the northeast in broad graceful curves, as indicated on the map, do not seem to be formed by the union of two marginal moraines, as is the rule in such instances, but appear to begin suddenly in the region bordering Main and Berg lakes. This apparent anomaly is due to the fact that the secondary glaciers in that region are wasting away and have already melted at their sources and left barren boulder-strewn areas, now filled in part with water held in check by ice still filling the main valley. These secondary glaciers have not only been *beheaded*, but a reverse flow initiated in the portion remaining. By observing the contour lines drawn on the map where they cross the ice in Main valley, it will be seen that the surface of the glacier has a slope both east and west from a divide.

The most remarkable feature in the behavior of the medial moraines shown on the map is the union of several trains of stones and dirt on White glacier and on Southeast tributary, where they come together and finally form a single ridge. This peculiar phenomenon has not been fully explained, but is probably due to a decrease in volume of the several streams by reason of their melting.

Dying glacier, on the west side of Muir inlet, presents decisive evidence of recent retreat. Its surface is almost completely concealed beneath dirt and stones, and the valley below its present terminus has recently been abandoned by the ice and is barren and desolate. Similar evidence of the general waste and recession that is affecting many of the glaciers of Alaska is also manifest in Dirt glacier. In this case the ice is so completely concealed by a superficial sheet of débris that one not familiar with the various phases of glacial waste would scarcely recognize it as a glacier at all. It appears more like a plowed field washed by winter storms than like an ice body.

Recent Recession.—In addition to the qualitative evidence of general glacial retreat indicated above, we have direct quantitative measures of the recession of the ice cliffs in which Muir glacier ends. As observed by Wright and Reid, Muir glacier has in recent years been both of greater and of less extent than at present. The fact of a former shrinking is shown by an abundance of evidence. The bases of the enclosing mountains and the summits of the rocky islands in the glacier are smoothed and striated, and have boulders of various kinds of rocks scattered over their slopes. These results of ice action reach, in vertical height, about 2000 feet on the sides of the mountain near where Muir glacier now terminates, and extend far south along the shore of Glacier bay. The absence of trees, and the general desolation of the borders of Glacier bay and of all the valleys opening from it, are in marked contrast to the densely wooded shores of neighboring inlets, and are due to the recent occupation of the region by glacial ice.

If the ice at the locality where Muir glacier now ends were 2000 feet thicker than at present, making its total depth about 3000 feet, as was the case when its maximum extension occurred, it is evident that its terminus would be far to the south. At the time of the greatest extension, all of the glaciers now pouring into Glacier bay were united and formed a trunk stream which flowed southward and probably united with other similar ice sheets so as to form a piedmont glacier. This great extension was during one of the later maxima of the glacial epoch. There is evidence, however, of an extension of the ice far beyond its present limits within the past one hundred years.

In 1794, Vancouver sailed through Icy strait and failed to discover what is now known as Glacier bay, but states that a wall of ice existed at its present entrance. The evidence that Vancouver actually saw the

terminus of the Glacier bay ice sheet is not conclusive, as his description would apply equally well to a jam of bergs closing the entrance of the inlet. When taken in connection with similar evidence of ice extension in Disenchantment bay, 150 miles to the west, it seems reasonable to suppose, however, that at the time of Vancouver's visit Glacier bay was actually occupied by a great glacier.

Observations on the position of the terminus of Muir glacier made by Muir in 1879, show that the ice then extended about one and three-fourths miles, and when seen by Wright in 1886, about one mile below the position of its extremity when surveyed by Reid in 1890. Still more recent observations indicate that this rapid retreat, with many variations in the trend of the ice cliffs, is still in progress.[1]

Glaciers on the West Side of Glacier Bay.

But little is known of the glaciers entering Glacier bay from the west, excepting that they are of large size and set vast quantities of ice afloat. The thunder of avalanches in that region may be heard while ascending the bay, but the ice floes about the fronts of the glaciers are usually so closely packed that, so far as I have been enabled to learn, no vessel has made a near approach to them. Muir explored this portion of the bay in a canoe, and states that next to Muir glacier, the largest ice stream entering it is at the northwestern extension. The glacier referred to is probably the one now known as Pacific glacier. As described by Muir, "its broad, majestic current, fed by unnumbered tributaries, is divided at the front by an island, and from its long, blue wall the icebergs plunge and roar in one eternal storm, sounding day and night, winter and summer, and from century to century."

The glaciers on the west side of Glacier bay present a most attractive field for study and are within easy reach of lines of summer travel. Results as valuable as those gathered by Wright and Reid might there be had during one or two summer excursions.[2]

Another tide-water glacier is reported to exist at the head of Dundas bay, opening into Cross sound to the west of Glacier bay, but there are no authentic observations available concerning its character and extent.

[1] A discussion of observations bearing on the rate of retreat of Muir glacier is given by Reid in The National Geographic Magazine, Washington, D.C., vol. 4, 1892, pp. 37–42.

[2] Since this was written I have learned that Reid made a study of the glaciers on the west side of Glacier bay in 1892. An account of these observations, together with a valuable map, showing all of the glaciers that reach the sea in that region, will soon be published in the 16th Annual Report of the U. S. Geological Survey.

Proceeding westward from Cross sound along the sublime Fairweather coast, the next glacier met with which discharges directly into the sea, is at the head of Disenchantment bay, 150 miles from Muir glacier and about 50 miles eastward of Mount St. Elias.

Glaciers of Disenchantment Bay.

(See map forming Plate 17.)

On the shore of the narrow, winding inlet at the head of Yakutat bay, known as Disenchantment bay, there are three glaciers which enter the water and give origin to bergs, and at least a score of lesser ice streams that have recently shrunken and are now separated from the bay by narrow and exceedingly barren boulder-strewn areas. On the higher portions of the mountains enclosing this land-locked arm of the sea, there are hundreds of alpine glaciers descending from shining snow fields. The tide-water glaciers referred to are the Turner, Hubbard, and Nunatak. The positions of their extremities are shown approximately on the sketch map forming Plate 17.

Turner, Hubbard, and Nunatak Glaciers. — The best general idea of the ice streams discharging into Disenchantment bay can be obtained from the islands that break its surface. The largest of these, named Haenke island in honor of the botanists of Malaspina's expedition, during which portions of the southern coast of Alaska were explored in 1792, was visited by the writer in 1890, and a landing effected with some difficulty through the closely packed icebergs that beset its shores. Its borders are high and rocky. Its surface has been worn into rounded and subdued contour by the ice that once flowed over it, with a depth of about 2000 feet. The domes of light-colored granite are smooth and polished, and give abundant evidence of the stubborn resistance they offer to the ice current. The summit of the island is about 800 feet above the surrounding waters.

The following account of the tide-water glaciers to be seen from Haenke island is taken from the report of my first expedition to Mount St. Elias:[1]

"Reaching the topmost dome of Haenke island, a wonderful panorama of snow-covered mountains, glaciers, and icebergs lay before us. The island occupies the position of the stage in a vast amphitheatre; the

[1] National Geographic Magazine, Washington, D.C., vol. 3, pp. 98, 99.

spectators were hoary mountain peaks, each a monarch robed in ermine and bidding defiance to the ceaseless war of the elements. How insignificant the wanderer who confronts such an audience, and how weak his effort to describe such a scene!

"From a wild cliff-enclosed valley toward the north, guarded by towering pinnacles and massive cliffs, flows a great glacier, the fountains of which are far back in the heart of the mountains beyond the reach of vision. Having vainly sought an Indian name for this ice stream I christened it Dalton [Turner] glacier.[1] The glacier is greatly shattered and pinnacled in descending its steep channel, and on reaching the sea it expands into a broad ice foot. The last steep descent is made just before gaining the water, and is marked by crevasses and pinnacles of magnificent proportions and beautiful color. This is one of the few glaciers of the Mount St. Elias region that has well-defined medial and lateral moraines. At the base of the cliffs on the western side there is a broad lateral moraine, and in the center, looking like a winding road leading up the glacier, runs a triple-banded ribbon of débris, forming a typical medial moraine. The morainal material carried by the glacier is at last deposited in the sea at its foot or floated away by icebergs and scattered far and wide over the bottom of Disenchantment and Yakutat bays.

"The glacier expands on entering the water, as is the habit of all glaciers of clear ice when unconfined, and ends in magnificent ice cliffs some two miles in length. The water dashing against the bases of the cliffs dissolves them away, and the tide tends to raise and lower the expanded ice foot. The result of these agencies and of the onward flow of the ice itself is to cause huge masses, sometimes reaching from summit to base of the cliffs, to topple over into the sea with a tremendous crash. Owing to the distance of the glacier from Haenke island, we could see the ice fall long before the roar it caused reached our ears; the cliffs separated and huge masses seemed to sink into the sea without a sound; the spray thrown up as the blue pinnacles disappeared ascended like gleaming rockets, sometimes as high as the tops of the cliffs, and then fell back in silent cataracts of foam. Then a noise as of a cannonade came booming across the waters and echoing from cliff to cliff. The roar of the glacier continues all day when the air is warm and the sun is bright, and is most pronounced when the summer days are finest. Sometimes roar succeeds roar like artillery fire, and the salutes were answered, gun

[1] The U. S. Board of Geographic Names has for sufficient reason authorized the substitution of the name of J. H. Turner for the name originally given by me.

for gun, by the great Hubbard glacier, which pours its flood of ice into the fiord a few miles northeast of where Turner glacier terminates. This ice stream, the most magnificent of the tide-water glaciers of Alaska yet discovered (with the exception, as is now known, of the southwest prolongation of Malaspina glacier), and a towering mountain peak from which it receives a large part of its drainage, were named in honor of Gardiner G. Hubbard, president of the National Geographic Society. A dark headland on the shore of the mainland to the right shuts off the full view of the glacier, but formed a strongly drawn foreground, which enhanced the picturesque effect of the scenery."

A year later, on September 6, I renewed the exploration of Disenchantment bay. With two companions I rowed northward near the base of the cliffs to the east of Haenke island. We found the bay quite free from floating ice, although the bergs were densely packed against the western shore. The morning was bright and fresh after prolonged storms, but dense cloud masses still clung to the cold summits of the higher mountains. The vegetation on the rugged shores became more and more stunted as we advanced. Before reaching Osier island, situated at the abrupt angle formed where Disenchantment bay turns eastward, even the more sheltered gorges were barren and desolate down to within 100 feet of the water's edge. At Osier island there is an outstanding cape, forming an island at high tide, which is covered with a dense growth of stunted willows, — hence its name, — and affords a fine station for observing the magnificence of the surrounding glaciers and mountains.

Seated among the willows on the summit of the island, we noted the luxuriance of the grasses at our feet and the profusion of dwarf raspberries, *Rubus arctica,* which were just ripening. We were at the actual border of vegetation. All to the north was stern, wild, and desolate. Cliffs and precipices without the softening tints of plant life rose precipitously from the water's edge to the snow-covered slopes which disappeared in the clouds. Just across the inlet, perhaps two miles distant, rose the ice cliffs of Hubbard glacier to a height, by estimate, of 250 to 300 feet. Each shining buttress and glittering pinnacle, as seen in the early morning light, was of the purest white or of the most delicate blue, while the caves and deep recesses were of such a deep blue that they appeared black in contrast with the sheen of the surfaces where the sunlight fell. Reports like the roar of heavy guns frequently attracted our attention to the cliffs, but owing to their distance, the avalanches causing the disturbances usually disappeared before the sound reached our station.

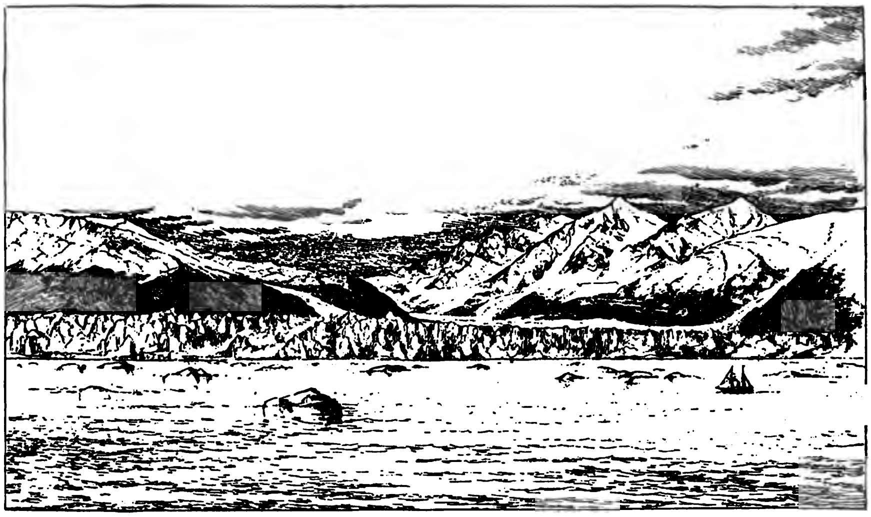


FIG. A.—HUBBARD GLACIER, DISENCHANTMENT BAY, ALASKA.

(Drawn from a Photograph.)

FIG. B.—GLACIATED SURFACE OF HAENKE ISLAND, DISENCHANTMENT BAY, ALASKA, LOOKING NORTH.

Following the reports came the waves generated by the falling ice masses, which broke on the beach in long lines of foam. The surface of the bay was unruffled by wind, and the breaking of these occasional surges seemed a phenomenon without a cause, until their connection with the masses of ice falling from the glacier was suggested.

Both Turner and Hubbard glaciers are in full view from Osier island, as are also many lesser ice streams that do not reach the sea. The lower extremity of all of the smaller glaciers that approach the sea are completely concealed beneath brown and barren moraines. Many times these sheets of débris are so uniform, and merge with the surrounding boulder-covered area so gradually, that it is impossible to tell where the glaciers actually terminate.

During our exploration of Disenchantment bay, we sailed eastward along the coast to where the inlet abruptly changes its course and extends southward through the mountains and into the flat, forest-covered alluvial plain bordering the Pacific. At the angle where the bay makes this sharp bend there is a high, rocky promontory of glacier-burnished rock, which I named Cape Enchantment. From the summit of this headland another splendid view of the mountain-enclosed bay was obtained. At the extreme eastern end of the east-and-west reach of the bay, a large glacier comes down to the water, and breaking off sends many bergs adrift. This glacier was not explored, but evidently flows from snow fields far back in the highlands. Near where it discharges into the bay it is divided by a rounded dome of rock which rises through the ice and forms a *nunatak*, as such islands in ice are called in Greenland, which suggested the name Nunatak glacier.

Many other facts of interest to the student of glaciers may be observed from Haenke and Osier islands and from Cape Enchantment, some of which are described elsewhere.[1] As our immediate interest is concentrated on tide-water glaciers we must pass on, in our fireside travels, to the next example, to the west of Yakutat bay, which is by far the most magnificent of its class yet found in Alaska.

Icy Cape.

All of the tide-water glaciers of Alaska referred to above reach the waters of the ocean at the heads of deep inlets or fiords, and are sur-

[1] "An Expedition to Mount St. Elias, 1890," National Geographic Magazine, vol. 3, 1891, pp. 53–203. "Second Expedition to Mount St. Elias, 1891," 13th Annual Report U. S. Geological Survey, pp. 1–91.

rounded by precipitous mountains. At Icy cape, however, the western lobe of Malaspina glacier advances boldly into the Pacific and meets the full force of its surges. There are no highlands bordering the ocean for scores of miles on either hand, and the glittering wall of ice rises above the foaming waters to a height not less than three hundred feet. The general appearance of these great precipices of ice when seen at a distance recall the chalk cliffs of Dover, but are more varied in color and far more impressive. The heavy waves of the Pacific undermine the cliffs, and great masses of ice are almost continually falling into the sea. Their thunder is seldom silent, and on still days can be heard distinctly at a distance of twenty miles.

The scene presented by Icy cape, with its white girdle of floating bergs, especially when a storm is raging and the heavy billows add their roar to the thunder of the avalanches, is one of the wildest and grandest that can be imagined.

The ice cliffs formed where Malaspina glacier enters the sea present only one of the many interesting features of the great ice sheet at the southern base of Mount St. Elias. This great glacier is the type of piedmont ice sheets, and will be described a few pages in advance.

To the west of Icy cape there are other great glaciers intervening between the mountains and the sea. The largest of these, known as Bering glacier, is probably of the same character as the Malaspina ice sheet, but no one has trodden its surface and scarcely anything is known concerning even its more general features. So far as has been reported, there are no glaciers to the west of Icy cape which actually reach the sea, and therefore none that require mention at the present time.

Alpine Glaciers.

Several of the alpine glaciers of Alaska which enter the sea have already been partially described under the head of tide-water glaciers; but there are others, numbering many hundred and probably several thousand, that terminate before reaching the sea, and belong to the class here considered. Nearly all of the higher valleys and depressions among the mountains from Stikine river northward and westward to Cook's inlet are filled with névé snows and drained by ice streams. This great glacial belt, nearly a thousand miles in length, has its maximum width in the vicinity of Mounts Fairweather, Logan, and St. Elias, where it is from 80 to 100 miles wide. Over this central territory, about 350 miles in length,

every depression at an elevation of over a thousand feet, is filled with snow and ice, making one confluent névé field, through which the higher and more rugged peaks rise like barren islands. An extended view of this wild country, where so many glaciers have their sources, was obtained by the writer in August, 1891, from the northern side of Mount St. Elias, and may be taken as representing the general character of the entire region between Lynn canal and Copper river. My report on the portion of the climb referred to is as follows[1]:

"I was now so near the crest of the divide that only a few yards remained before I should be able to see the country to the north, a vast region which no one had yet beheld. As I passed on, I pictured in fancy its character. Having previously crossed this same system of mountains at the head of Lynn canal and traversed the country north of it, I imagined I should behold a similar region north of Mount St. Elias. I expected to see a comparatively low, forested country, stretching away to the north, with lakes and rivers and perhaps some signs of human habitation; but I was entirely mistaken. What met my astonished gaze was a vast snow-covered region, limitless in expanse, through which hundreds and perhaps thousands of barren, angular mountain peaks projected. There was not a stream, not a lake, and not a vestige of vegetation of any kind in sight. A more desolate or a more utterly lifeless land one never beheld. Vast smooth snow surfaces, without crevasses, stretched away to limitless distances, broken only by jagged and angular mountain peaks. The general elevation of the snow surface is about 8000 feet, and the mountains piercing it are from 10,000 to 12,000 feet, or more, in altitude above the sea. Northward I could see every detail in the forbidding landscape for miles and miles. The most remote peaks in view in that direction were 40 or 50 miles distant. To the southeast rose Mount Fairweather, plainly distinguishable, although 200 miles away. About an equal distance to the northwest are two prominent mountain ranges, the highest peaks of which appeared as lofty as Mount Fairweather. These must be in the vicinity of Mount Wrangel, but their summits were unclouded and gave no token of volcanic activity.

"I could look down upon the coast about Yakutat bay and distinguish each familiar island and headland. The dark shade on the shore, too distant to reveal its nature, I knew was due to the dense forests on the lowlands between the mountains and the sea. This was the only

[1] "Second Expedition to Mount St. Elias, 1891," in 13th Annual Report U. S. Geological Survey, 1891-92, pp. 47, 48.

indication of vegetation in all the vast landscape that lay spread out beneath my feet. The few rocks near at hand, which projected above the snow, were without the familiar tints of mosses and lichens. Even the ravens which sometimes haunt the higher mountains were nowhere to be seen. Utter desolation claimed the entire land.

"The view to the north called to mind the pictures given by Arctic explorers of the borders of the great Greenland ice sheet, where rocky islands, known as 'nunataks,' alone break the monotony of the boundless sea of ice. The region before me was a land of nunataks."

It is impossible to give a detailed account of the great number of alpine glaciers in southern Alaska, but a few of those best known may be described, and serve as examples of the class to which they belong.

Seward Glacier. — The largest alpine glacier thus far discovered in North America, exclusive of the Greenland region, has its source in the neighborhood of Mount Logan, and was named the Seward glacier in honor of the distinguished Secretary, to whom we are indebted for the purchase of Alaska. It has many tributaries in the rugged region where it rises, and flows southward like a broad sluggish river to the Malaspina glacier, of which it is one of the principal feeders. A portion of this great glacier and some of its branches, is shown on the map forming Plate 16, but the entire area it drains has not been explored. A view of the glacier and of many of its tributaries was had by the writer from the summit of the Pinnacle cliffs, which embraced fully fifty miles of the ice stream and many of the magnificent peaks from which it receives the snow drainage. The glacier in its narrowest part is by estimate three miles broad. Except at a few places where it passes rocky precipices, its sides are poorly defined, as it merges with broad snow fields in such a manner that only the crevassed and broken condition of the snow on the sides of the more rapidly flowing central portion serves to define its boundaries. At three localities where it descends steep slopes due to faults in the rocks beneath, the ice is broken and stands in pinnacles between blue crevasses, but these ice falls are not as high or as impressive as in some of the neighboring glaciers. The first or upper fall, at the east end of the Corwin cliffs, is an abrupt descent of several hundred feet, and from the west appears like a huge wall crossing the glacier from side to side. Both above and below the fall the surface appears nearly level for several miles, and is as smooth and even as a snow-covered meadow. Some ten miles below the upper fall is the second ice cascade, or what may more properly be called

an ice rapid. The ice is there greatly crevassed for several miles, but retains a generall, level surface and its remarkably stream-like character. These rapids occur where the ice flows across an escarpment formed by a prolongation of Pinnacle cliffs.

On looking down on the rapids from a commanding summit, one beholds a series of breaks in the ice which are small at first and trend up stream from each margin of the central current. The first breaks to be recognized are mere cracks, and although approaching the center of the glacier, do not meet. A few rods below, the cracks are a little broader, and meet in the center of the glacier so as to form a continuous break from side to side. The fissures from either side meet at an angle of perhaps 50 or 60 degrees, and form V-shaped figures, with their apexes pointing up stream. A few rods farther down, the crevasses cross the glacier in nearly straight lines, and then begin to bow in the middle on account of the more rapid central current. The more rapid flow of the central portion of the stream is indicated throughout the descent by the curvature of the crevasses. After becoming gently curved down stream they pass into semilunar gashes, widest in the center and tapering towards the end. Finally, near the lower end of the rapid, the crescents become sharply bent in the center, and the bending increases until the gashes from either side unite at an angle of perhaps 30 degrees, and again form V-shaped figures, this time pointing down stream. With these progressive changes in the direction and size of the crevasses, cross fractures are formed, which become more and more numerous in the central and lower portions of the rapid. The parallel V-shaped gashes arranged in regular order, one above another, impart to the central part of the glacier a peculiar wavy appearance when seen from a distance, resembling the changeable figures to be seen in "watered ribbon." With these changes in the direction and size of the crevasses there are accompanying changes in color. The cracks in the upper part of the rapids are in a white surface, but the ice forming their walls is dark blue. At a distance the breaks appear as blue lines on the snow. Lower down stream, where the cracks become wider, broad white tables are left between them. As cross fractures are formed, the sides of the tables crumble away and portions falling into the crevasses tend to fill them up. As the surface melts, the surfaces of the tables lose their purity and become dust-covered and yellowish, but the broken blocks in the crevasses expose fresh material and retain their whiteness. At this stage, the sides of the crevasses change from blue to white. The positions of the breaks are then marked by broad, white bands on a gray surface. Far

down the rapids, where the lower set of V-shaped crevasses are most pronounced, the tables have crumbled away and filled the intervening gulfs, so that their positions are distinguished solely by differences in color. The scars of the crevasses formed above are shown by white bands on a dark, dust and dirt covered surface, instead of by blue markings on a white surface, as at the beginning. Before the lower ice fall is reached where the Seward glacier makes a final plunge before joining the Malaspina glacier, nearly all traces of the tens of thousands of fissures formed above have disappeared.

An observer standing on one of the commanding summits at the western end of Pinnacle cliffs can see the broad surface of Seward glacier from the upper falls to where it disappears over the brink of the lower fall on the border of Malaspina glacier. The glacier from side to side then drops from sight, and the wild assemblage of pinnacles that occurs below is only indicated by a line of blue where the final plunge begins. Such a view suggests the appearance of Niagara when seen from above the horseshoe fall, but the far mightier cascade in the Seward glacier is silent and apparently motionless.

The writer was encamped for several days in July, 1890, on a narrow crest of rock barely wide enough to support a small tent, which breaks through the snow at the western end of Pinnacle cliffs; and on the immediate border of the rapids is Seward glacier. The murmur of water flowing through icy channels could be heard far beneath the surface of the glacier, but no streams traversed its broken surface. Crashes and rumbling noises produced by the slowly moving mass frequently attracted our attention, and sometimes at night we would be awakened by a dull, heavy thud, accompanied by a trembling of the rocks on which we slept, and producing the effect of a slight earthquake shock. Occasionally a towering pinnacle of ice on the extremely rugged surface of the glacier in front of our tent would fall with a startling crash and be engulfed in an adjacent crevass. These evidences of change showed that the apparently motionless ice was in reality flowing onward. Changes in the relative positions of easily recognized points on the glacier and on the distant shore were noticed during various visits, but instrumental measurements of the rate of motion of various prominent pinnacles made by my assistant and myself failed to give satisfactory results.

When exploration shall be extended into the mountains clustering about Mount Logan and extending northward from Mount St. Elias, the Seward glacier will furnish the most promising highway of travel. The

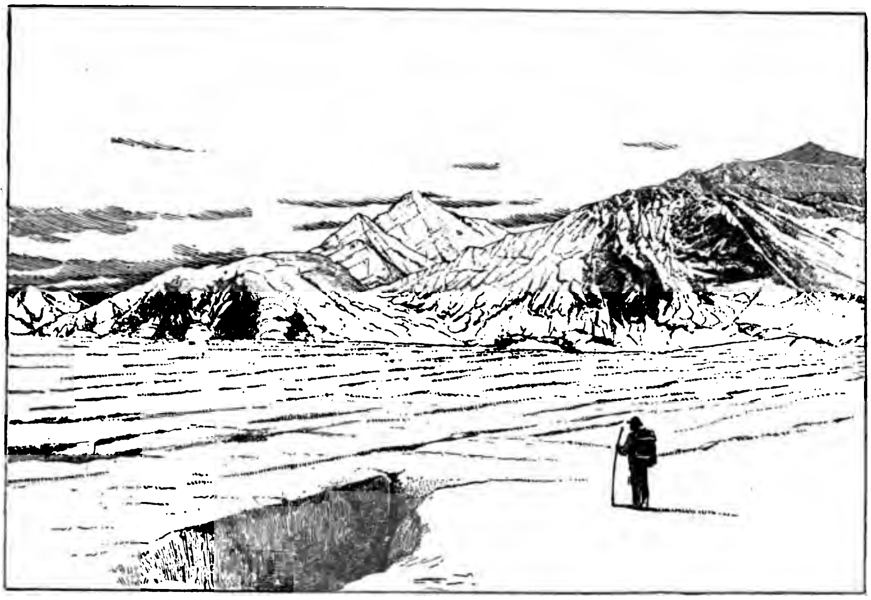


FIG. A.—SURFACE OF SEWARD GLACIER, ALASKA.

The summit of Mount St. Elias is seen in the distance, beyond the hills bordering the glacier. (Drawn from a Photograph.)

FIG. B.—DAVIDSON GLACIER, LYNN CANAL, ALASKA.

snow fields along the margins of the glacier where its surface is most broken afford easy lines of march, and the ice falls can be passed without serious difficulty by scaling the adjacent cliffs. When once above the upper fall the way is clear, and a broad, snow-covered surface affords a direct route to the immediate base of Mount Logan. In making this journey the explorer should pass around the southern end of the Hitchcock range and gain the Seward glacier just above the lower fall. When that point is reached the way ahead is well defined. By means of snow shoes and sleds drawn by dogs, an advance can be made for perhaps a hundred miles into the interior. By descending a glacier on the northern side of the mountains some stream could be reached which would carry the explorer again to the coast. The close of the winter season would probably be the best for this attractive journey, as the crevasses would then be deeply buried, and the rivers of the interior could be reached in time to descend them during the short summer.

Although Seward glacier is the largest ice stream yet discovered in Alaska, it does not differ materially from many others of the same type now known to exist in that region. It is the only glacier in the neighborhood of Mount St. Elias, however, which, so far as known, heads far back in the mountain and flows through a low-grade pass to the sea. The Hubbard glacier may have this characteristic, but as its gathering-ground has never been seen, its relation to the mountain cannot be definitely determined. The character of the surface of the Seward glacier is shown on Fig. A, Plate 16 ; the summit of the upturned mountain-block forming Mount St. Elias is seen beyond the hills forming the bank of the glacier.

The next large ice stream to the west of the Seward glacier is the Agassiz glacier, which drains the snow fields on the south side of the Augusta range and the eastern slope of Mount St. Elias. To the west of Mount St. Elias rises Guyot glacier, another of the great tributaries that unite to form the Malaspina ice sheet, the type of piedmont glaciers.

Glaciers of Lynn Canal.

It has been the writer's good fortune to make three trips through Lynn canal, each of which furnished many independent observations on the glaciers diversifying its shores. The first of these journeys was made in a canoe with a single Indian, while returning from an expedition up the Yukon river, an account of which has been published in the Bulletin

of the Geological Society of America.[1] The second and third journeys were made on steamers and were much less satisfactory than the first.

Taya Inlet. — Lynn canal divides near its head into two arms, known as Taya and Chilkat inlets. The first leads toward Chilhoot pass and the second toward Chilkat pass. Each of these arms, like the main trunk of Lynn canal, is bordered by high mountains, and receives many swift streams issuing from caves at the lower extremities of alpine glaciers. The larger glaciers drain broad névé fields which whiten the higher portions of the mountains throughout the year. The smaller ones have their sources in sheltered amphitheatres and cirques, but at times originate in snow fields that rest on the mountain side, and are so prominent that when seen in profile, they give a convex outline to the sides of the peaks about which they cluster.

From a mountain top about 3000 feet high, on the west side of Taya inlet, I obtained an extensive and most instructive view of the rugged mountains in which the blue tranquil waters of the great canal are embosomed. From one station I counted nearly forty glaciers, and a change in position of half a mile brought several others into view which before were concealed by rugged crags and snow-covered slopes near at hand. The outlines of vast amphitheatres in the mountain tops could be traced by lines of pinnacles and towering, frost-riven crags forming their rims, but the basins within were so deeply filled with snow and ice that one could walk across them with ease. Many of the views of the mountains enclosing Lynn canal, obtained from the decks of steamers, are truly magnificent, but fail to give such a comprehensive idea of the entire plan of the hundreds of snow-clad peaks, and of the deep valleys separating them, as the broad panoramas which reward the climber who reaches some of the less aspiring summits. Added to the sublime picture of snowy ranges and winding waterways obtained from such a station are wonderful cloud effects, to be seen especially when a storm gives way to clear skies and the last remnant of the vapory hosts that previously enshrouded the ranges still cling to the more lofty summits.

Davidson Glacier. — The finest glacier on Lynn canal, named in honor of Prof. George Davidson, of the U. S. Coast and Geodetic Survey, has its source in the rugged mountains between Lynn canal and Glacier bay, and flows from the same general névé fields that supply some of the principal tributaries of Muir glacier. A photograph of its expanded ex-

[1] Vol. 1, 1890, pp. 99–162.

tremity, as seen from a passing vessel, is reproduced in Fig. B, Plate 16. It finds its way eastward through a deep, high-grade gorge between lofty peaks, and reaches within a few score feet of sea level, but does not enter the waters of the canal so as to form a tide-water glacier. Moraines left by the glacier in its retreat, and alluvial material brought out from it by swift, heavily laden streams, have been deposited about the margin of the ice foot so as to form an encircling girdle now covered on its outer margin with a dense spruce forest. On passing from the beach through the forest for a distance of about a mile, one comes to a barren, desolate tract of boulders and gravel of fresh appearance, and evidently but recently abandoned by the glacier. The barren area is perhaps half a mile broad, and separates the extremity of the foot of the glacier throughout the entire periphery of its expanded terminus from the encircling forest. From archways in the ice there issue swift, roaring streams of muddy water, much too strong and too deep for one to wade. These streams are heavily loaded, and at once begin to deposit their burdens and to build up their channels, so that their courses are unstable and new distributaries are formed from time to time. Standing by the side of one of the streams as it issues from its icy cavern, one may hear the clash of the boulders that are swept along at the bottom of the turbid waters. The localities at which the streams emerge from the ice are changed from time to time, so that the entire area bordering the ice foot is torrent-swept and covered with stream-borne deposits.

The ice at the lower extremity of Davidson glacier has a crystalline appearance, much like coarsely crystallized dolomite. The banded structure generally so characteristic of glacial ice is not apparent in the exposed surfaces. On climbing the rough crags of ice forming the immediate foot of the glacier one finds stones and dirt scattered over its surface, but a definite arrangement of the superficial débris in medial and lateral moraines is not apparent in a near view. From a distance, however, as from the decks of passing vessels, well-characterized medial bands looking like roadways can be easily recognized, as well as broad, dirt-covered areas, answering to lateral moraines, at the bases of the enclosing cliffs.

During my canoe trip down Lynn canal in 1889, I was storm-bound for three days at Davidson glacier, and sought refuge in the sombre, moss-covered forest about its foot. One cannot fully appreciate the varied beauties of the dense forests of Alaska until he has actually lived in their depths and witnessed the many changes that the primeval wilderness presents during storms and sunshine. The trees are large and rugged, and

frequently clothed, even to the ends of their topmost branches, with dense coats of shaggy moss. Aged trunks long since dead and stripped of their foliage, but still standing, assume strange, weird shapes, due to the thick masses of mosses, lichens, and fungi that make their homes upon them. Mosses and lichens cover the ground as with a dense mat a foot or more thick, into which one sinks knee-deep at every step as if walking over a bed of wet sponges. The trunks of fallen sachems of the forests are buried from sight by a living mound of green and brown, most artistically decorated with flowers and ferns. Every rod that one advances into the moist and frequently mist-filled forests reveals new beauties, and fascinates the fancy with harmonies of form and color not exceeded by those of the moss-draped cypress and live-oak forests of Florida.

Along the shores of Lynn canal eastward from Davidson glacier, there are other ice streams that drain the shining snow fields on the mountains and add variety and beauty to the splendid scenery of that justly famed arm of the sea; but none of them reach tide water. The extremities of the larger glaciers are hidden behind fringes of forests growing on the deposits laid down during their slow retreat. To an observer on passing vessels, the steep, broken surfaces of the ice streams, as they descend precipitous slopes, may be seen above the green of the forests into which they seem to plunge. When the summits of the mountains are enshrouded in mist the precipices of ice appear like frozen cataracts descending from the clouds. The glaciers of Lynn canal that rank next to Davidson glacier in size and beauty are the Auk, Eagle, Lemon creek, and Juneau. These are all on the northeastern shore, and are better known than those on the opposite coast because of their proximity to the beach. There are, besides, hundreds of nameless glaciers that would well repay individual study, of which glimpses may be had by those who pass in a day.

Glaciers of the Interior of Alaska.

In traversing the deep valleys leading from the head of Lynn canal to Chilkoot and Chilkat passes, one sees small glaciers on the adjacent mountains. After passing the divide between the waters flowing directly to the Pacific and those tributary to the rivers of the interior, other similar glaciers occur which descend the northern slope of the mountains. The timber line in the interior is far below the limit reached by the glaciers, and the intervening area is barren and rugged, and strewn with débris left by former ice streams. In the clefts between the more lofty

summits rising above the barren area, there are tongues of ice that descend from snow fields, filling elevated valleys and amphitheatres about the crests of the mountains. These glaciers all of the alpine type, are usually of comparatively small size, and are the sources of many swift streams of turbid water. Their extremities are seldom lower than 3000 or 4000 feet above sea level.

The general features of the region draining northward in the vicinity of Lynn canal are believed to be characteristic of an extended belt of imperfectly explored country along the inland slope of the mountains bordering the coast. Bold explorations made to the westward of Chilkat pass, by E. J. Glave in 1890, and again in 1891, show that in the region drained by Alsek river — a wild, impetuous stream flowing through the mountains bordering the coast — and by numerous tributaries of the Yukon, there are many alpine glaciers of the same general character as those already referred to at the head of Chilkat pass.

Our knowledge of the glaciers draining to the interior was much extended in the summer of 1891 by important explorations made by Dr. C. Willard Hayes[1] in company with Lieut. Frederick Schwatka. This expedition ascended Taku inlet, and after crossing a low divide reached the head waters of the Yukon, and descended that stream in boats to Selkirk house. Thence an overland journey was made westward to Copper river, and an extended region explored on the northern flanks of the mountains culminating in Mount Logan and Mount St. Elias. On gaining Copper river the expedition descended that stream to the coast, and confirmed the report of Lieut. H. T. Allen[2] in reference to the presence of glaciers near the sea. The principal glaciers examined by Hayes lie at a distance of 50 to 80 miles to the north and northwest of Mount St. Elias, and are described by him as follows in the paper just cited:

"Three large glaciers flow into the White River basin west of the Alaskan boundary; and numerous streams, crossed while following the southern bank of the upper White river, rise in small glaciers which do not descend to the level of the valley.

"The largest glacier known to discharge wholly in the Yukon basin is one which lies approximately on the 141st meridan, called the Klutlan, from the native name of the river to which it gives rise. Its source is in

[1] "An Expedition to the Yukon District," in National Geographic Magazine, vol. 4, 1892, pp. 117–162.

[2] "Report of an Expedition to the Copper, Tanana, and Koyukuk Rivers, Alaska," Washington, 1887, pp. 37–43.

the great snow fields between Mount St. Elias and the high peaks on the northern border of the range called *Nat-azh-at* by the natives. It extends several miles beyond the foot of the range, though it is rapidly receding at the present time, and is between four and five miles broad where it enters the valley. The stagnant ice in front of the retreating glacier is buried under a great accumulation of morainal material continuous with the terminal moraine, so that it is impossible to determine the exact limits of the ice. The heavy mantle of vegetation which covers the terminal moraine continues a mile or more beyond the outer edge of the ice, becoming gradually less abundant as the active portion of the glacier is approached.

"The moraine in front of the Klutlan is the largest accumulated by any of the interior glaciers. It is composed very largely of the white volcanic tufa already described, but with this are mingled many angular fragments of amygdaloid lava and a few of granite and gneiss. Much of the moraine has been removed by streams flowing from the glacier, but remnants 200 feet or more in thickness extend nearly across to the highland north of the valley.

"The second of the White River glaciers is about midway between the Klutlan and Scolai pass. It is much smaller than the Klutlan and does not push out into the valley, but its front forms a wall of ice something over a mile in length from side to side of the narrow valley in which it lies.

"The third and largest of the interior glaciers flows from the high mountains northwest of Mount St. Elias down into Scolai pass, and from the divide sends a lobe of ice toward White river and a smaller one toward Copper River basin. This was named in honor of Mr. I. C. Russell. The northern or White River lobe of Russell glacier is buried under a heavy accumulation of moraine bearing some vegetation, while the southern lobe is almost wholly free from morainal material, and the exposed ice has melted down to the smooth convex surface and feather edge characteristic of stagnant ice at the front of a retreating glacier."

Taken altogether, the ice flowing northward from the St. Elias mountains is insignificant in amount when compared with the vast frozen flood that pours down through every valley, cañon, and ravine on the southern slope of the same uplift. The Seward glacier alone probably contains a greater volume of ice than all the glaciers flowing into the White River basin combined.

Space will not permit me to quote more fully from Dr. Hayes' instructive description of the glacier seen by him, or to follow his discussion of the

climatic condition on which the distribution of the glaciers of Alaska depends. His explorations defined the northern limit of the present ice drainage and furnished additional information concerning the extent inland of the glaciers of the same region in former times.

ABSENCE OF GLACIERS IN CENTRAL AND NORTHERN ALASKA.

In the interior of Alaska and of the adjacent portion of Canada, there are many mountains that reach elevations of at least four or five thousand feet above the sea, but are bare of snow during the summer, and no glaciers are known to exist upon them. This fact is the more striking for the reason that several of the peaks referred to are near, and some of them even north of the Arctic circle, and might be supposed to afford favorable conditions for ice accumulation. A good illustration is thus furnished of the conclusion long since reached, that the existence of perennial ice does not necessarily depend upon latitude. The snow line when traced from the most southerly peak in California that is snow-capped in summer, northward along the Cordilleras, becomes lower and lower, until at the base of Mount St. Elias it is only 2500 feet above the sea. North of the St. Elias mountain belt, however, it rises abruptly, and so far as known is not reached by any elevations in the interior.

The reason for the apparent anomaly in the distribution of the glaciers of Alaska is to be found mainly in the direction of the currents of the Pacific and in the topography of the land. A warm ocean current, known as the Japan current, corresponding in many ways with the Gulf stream, impinges on the southern shore of Alaska and greatly modifies the condition of the atmosphere. The warm, humid winds from the south, in passing over the mountains near the coast, part with a large share of their moisture and descend to the lower regions to the north as comparatively dry winds. The snowfall on the mountains adjacent to the coast is excessive, while in the interior it is light. At elevations exceeding 8000 or 10,000 feet on the mountains near the sea every storm throughout the year is accompanied with snow, and above 13,000 feet it is safe to say that rain never falls. In the interior, however, not only is a snowstorm in summer unknown, but rain seldom falls during that season. In winter the prevailing air currents of the interior are from the frozen sea to the northward, and are in general dry winds, for the reason that they travel from cold to warmer regions and tend to absorb rather than to precipitate moisture. The mean annual temperature, and

still more markedly the mean winter temperature of the interior, is far below what it is at corresponding elevations on the coast, but, for reasons already stated, this is not necessarily favorable to the accumulation of perennial snow.

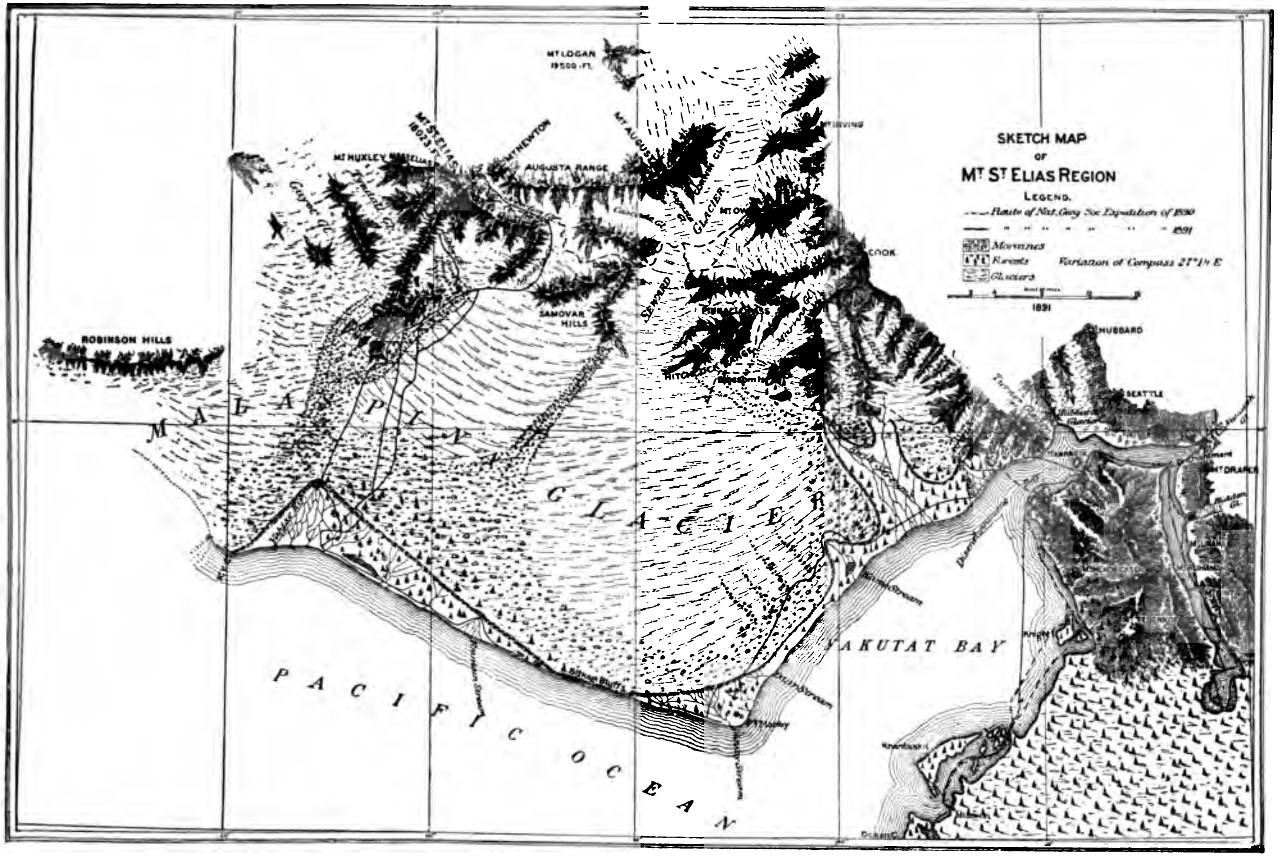
The glaciers of Alaska illustrate the well-known fact that the most favorable conditions for ice accumulation are found where a region of condensation is adjacent to a region of active evaporation.

The influence of climatic and topographic conditions on the existence of glaciers, just referred to, is again strikingly shown in the far northwest by the records of former periods of maximum ice extension. During the glacial period the ice fields adjacent to the Pacific were more extensive than at present, but were confined to the same general region. The glaciers that flowed northward in the vicinity of Mount St. Elias reached only about 100 miles inland. All of the central and northern portions of Alaska were unglaciated.

Glaciers of the Alaskan Peninsula and the Aleutian Islands.

Glaciers of the alpine type similar to those on the shores of Lynn canal are known to exist in the mountain-enclosed valleys on the border of Cook's inlet, and, in diminishing numbers and decreasing size, from there westward on the Alaskan peninsula and on some of the more rugged of the Aleutian islands. The positions of a few small glaciers on the borders of Cook's inlet are shown on the charts published by the U. S. Coast and Geodetic Survey, but no description of them has ever been published. The verbal reports of traders and hunters who have visited that region indicate that the snow fields crowning the mountains are extensive and that the glaciers flowing from them are well worthy of consideration. The snow line appears to have an elevation of some three or four thousand feet, and the glaciers are mostly individual tongues of ice descending to within a few hundred feet of the sea. None of them now reach tide water.

The most extensive of the isolated snow fields on the Aleutian islands yet reported cluster about the summit of Mount Makushin, the highest peak on Iluliuk island. A view of that imposing peak rising white and shining above a most rugged setting of lesser mountains, obtained by the writer from a commanding summit on the eastern portion of the same island, showed that the glaciers on its sides are small and similar in many ways to those of the High Sierra. Their lower limit appears to be about



Approximate scale: one inch = sixteen miles.

4500 feet above the sea, but the distance rendered it impossible to determine special characteristics. Some of the volcanic piles on the Aleutian islands to the west of Iluliuk are higher than Mount Makushin, and are known to be snow-covered in summer; but no definite information in reference to the presence of glaciers on them is available. It is to be expected that the great Cordilleran glacier belt, when traced westward from peak to peak on the Aleutian islands, will rise higher and higher, and that the glacier will at the same time diminish in size, until at last the topographic and climatic conditions will preclude their existence. Where the extreme western tip of the crescent formed by the Cordilleran glacier belt actually terminates remains to be determined.

Piedmont Glaciers.

Some account has already been given of the alpine glaciers on the southern slope of the mountains that culminate in Mount Logan and Mount St. Elias. Many of these ice streams descend onto a low plain intervening between the mountains and the sea, and there expand and unite one with another, so as to form vast lake-like bodies of ice to which the term piedmont glaciers has been applied. Two broad ice sheets of this nature, named in honor of the distinguished navigators Malaspina and Bering respectively, are now known, but only the former has been visited. Bering glacier has been seen from vessels passing along the coast to the westward of Mount St. Elias, but no explorer has as yet set foot upon it.

Malaspina Glacier.

(A sketch map of Malaspina glacier forms Plate 17.)

Area. — The Malaspina glacier, as indicated on Plate 17, extends with unbroken continuity from Yakutat bay 70 miles westward, and has an average breadth of between 20 and 25 miles. Its area is approximately 1500 square miles, or intermediate in extent between the area of the state of Rhode Island and the area of the state of Delaware.

It is a vast, nearly horizontal plateau of ice. The general elevation of its surface at a distance of five or six miles from its outer border is about 1500 feet. The central portion is free from moraines or dirt of any kind, but is rough and broken by thousands and tens of thousands of crevasses. Its surface, when not concealed by moraines, is broadly undulating, and recalls the appearance of the rolling prairie lands west of the Mississippi.

From the higher swells on its surface one may see for many miles in all directions without observing a single object to break the monotony of the frozen plain. So vast is the glacier that, on looking down on it from elevations of two or three thousand feet above its surface, its limits are beyond the reach of vision.

Lobes. — The glacier consists of three principal lobes, each of which is practically the expansion of a large tributary ice stream. The largest has an eastward flow, toward Yakutat bay, and is supplied mainly by the Seward glacier. The next lobe to the west is the expanded terminus of the Agassiz glacier ; its current is toward the southwest. The third great lobe lies between the Chaix and Robinson hills, and its main supply of ice is from the Tyndall and Guyot glaciers. Its central current is southward. The direction of flow in the several lobes explains the distribution of the moraines about their borders.

The Seward lobe melts away before reaching Yakutat bay and ends with a low frontal slope, but its southern margin has been eaten into by the ocean, so as to form the Sitkagi bluffs. The Agassiz lobe is complete, and is fringed all about its outer border by broad moraines. The Guyot lobe pushes boldly out into the ocean, and, breaking off, forms magnificent ice cliffs.

Characteristics of the Non-moraine-covered Surface. — On the northern border of the glacier, but below the line of perpetual snow, where the great plateau of ice has a gentle slope, the surface melting gives origin to hundreds of rills and rivulets which course along in channels of clear ice until they meet a crevasse or moulin and plunge down into the body of the glacier to join the drainage beneath. On warm summer days, when the sun is well above the horizon, the murmur of streams may be heard wherever the ice surface is inclined and not greatly broken ; but as soon as the shadows of evening cross the ice fields, melting ceases and the silence is unbroken. These streams are always of clear, sparkling water, and it is seldom that their channels contain débris. Where the surface of the glacier is nearly level, and especially when broken by crevasses, surface streams are absent, although the clefts in the ice are frequently filled with water. The moulins in which the larger of the surface streams usually disappear are well-like holes of great depth. They are seldom straight, however, as the water in plunging into them usually strikes the opposite side and causes it to melt away more rapidly than the adjacent

FRONT OF MALASPINA GLACIER, NEAR ICE BAY, ALASKA.

The glacier is covered with moraines on which a forest is growing.

surfaces. The water in descending is dashed from side to side and increases their irregularities. A deep roar coming from the hidden chambers to which the moulins lead frequently tells that large bodies of water are rushing along the ice caves beneath. In the southern portion of the glacier, where the ice has been deeply melted, and especially where large crevasses occur, the abandoned tunnels made by englacial streams are sometimes revealed. These tunnels are frequently 10 or 15 feet high, and occasionally one may pass through them from one depression in the glacier to another. In some instances they are floored with débris, some of which is partially rounded. As melting progresses this material is concentrated at the surface as a moraine.

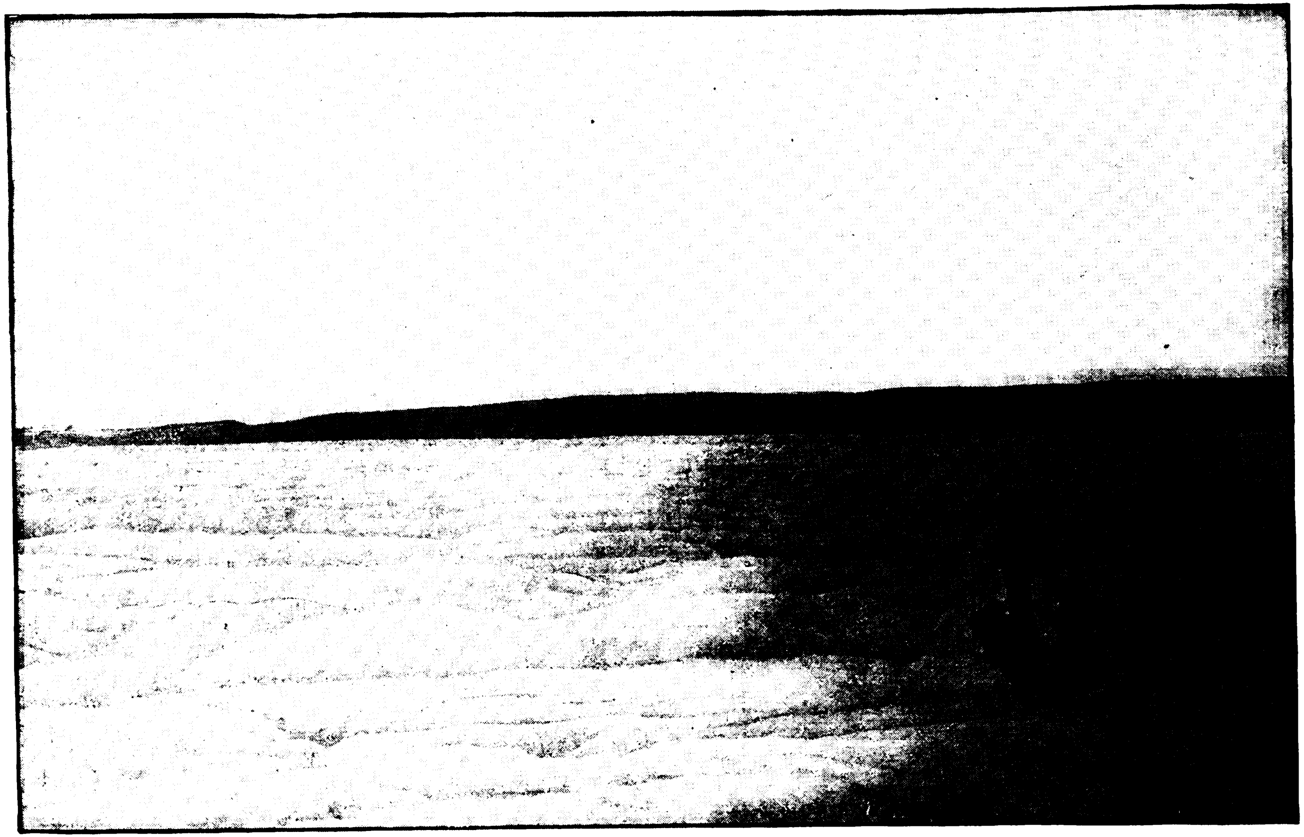
The ice in the various portions of the glacier was observed to be formed of alternate blue and white bands, as is the rule in glacial ice generally. The blue bands are of compact ice, while the white bands are composed of ice filled with air cavities. The banded structure is usually nearly vertical, but the dip, when noticeable, is northward. Nearly parallel with the blue and white layers, but crossing them at low angles, there are frequently bands of hard, blue ice several hundred feet long and two or three inches in thickness which have a secondary origin, and are due to the freezing of waters in fissures.

The rapid melting of the surface produces many curious phenomena, which, as explained in a previous chapter, are common to many ice bodies below the line of perpetual snow. The long belts of stone and dirt forming the moraines protect the ice beneath from the action of the sun and air, while adjacent surfaces waste away. The result of this differential melting is that the moraines become elevated on ridges of ice. The forms of the ridges vary according to the amount and character of the débris resting upon them. In places they are steep and narrow, and perhaps 150 or 200 feet high. From a little distance they look like solid masses of débris, and resemble great railroad embankments, but on closer examination they are seen to be ridges of ice, covered with a thin sheet of earth and stones. The sides of such ridges are exceedingly difficult to climb, owing to the looseness of the stones, which slide from beneath one's feet and roll down the slopes. The larger boulders are the first to be dislodged by the melting of the ice, and rolling down the sides of the ridges, form a belt of coarse débris along their margins. In this way a marked assortment of the débris in reference to size and shape frequently takes place. In time the narrow belts of large boulders become elevated in their turn and form the crests of secondary ridges. Rocks rolling down

the steep slopes are broken into finer and finer fragments and are reduced in part to the condition of sand and clay. When the débris is sufficiently comminuted it is sometimes carried away by surface streams and washed into crevasses and moulins. Not all of the turbidity of the subglacial streams can be charged to the grinding of the glacier over the rocks on which it rests, as a limited portion of it certainly comes from the crushing of the surface moraines during their frequent changes of position.

Isolated blocks of stone lying on the glacier, when of sufficient size not to be warmed through by the sun's heat in a single day, also protect the ice beneath and retain their position as the adjacent surface melts, so as to rest on pedestals frequently several feet high. These elevated blocks are usually flat, angular masses, sometimes 20 feet or more in diameter. Owing to the greater effect of the sun on the southern side of the columns which support them, the tables are frequently inclined southward, and ultimately slide off their pedestals in that direction. No sooner has a block fallen from its support, however, than the process is again initiated, and it is again left in relief as the adjacent surface melts. The many falls which the larger blocks receive in this manner cause them to become broken, thus illustrating another phase of the process of comminution to which surface moraines are subjected. On Malaspina glacier the formation of glacial tables is confined to the summer season. In winter the surface of the glacier is snow-covered and differential melting cannot be marked. The fact that glacial tables are seldom seen just after the snows of winter disappear suggests that winter melting takes place to some extent, but in a different manner from what it does in the summer. Just how the blocks are dislodged from the pedestals in winter has not been observed.

While large objects lying on the surface of the glacier are elevated on pedestals in the manner just described, smaller ones, as is well known, and especially those of dark color, become heated by the sun, and melting the ice beneath, sink into it. When small stones and dirt are gathered in depressions on the surface of the glacier, or on a large scale, when moulins become filled with fine débris and the adjacent surface is lowered by melting, the material thus concentrated acts as do large boulders, and protects the ice beneath. But as the gravel rises in reference to the adjacent surface, the outer portion rolls down from the pedestal on all sides, and the result is that a sharp cone of ice is formed, having a sheet of gravel and dirt over its surface. These sand cones, as they are called, sometimes attain a height of ten or twelve feet, and form conspicuous and characteristic features of the glaciers over large areas.



CENTRAL PORTION OF MALASPINA GLACIER ALASKA.

The surface of Malaspina glacier over many square miles, where free from moraine, is covered with a coral-like crust, which results from the alternate melting and freezing of the surface. The crevasses in this portion of the vast plateau are seldom of large size, and owing to the melting of their margins, are broad at the surface and contract rapidly downward. They are in fact mere gashes, sometimes 10 or 20 feet deep, and are apparently the remnants of larger crevasses formed in the glaciers which flow down from the mountains. Deeper crevasses occur at certain localities about the border of the glacier, where the ice at the margin falls away from the main mass; but these are seldom conspicuous, as the ice in the region where they occur is always heavily covered with débris and the openings become filled with stones and boulders. The generally level surface of the glacier and the absence of large crevasses indicate that the ground on which it rests is comparatively even. Where the larger of the tributary glaciers join it, however, ice falls occur, caused by steep descents in the ground beneath. These falls are just at the lower limit of perpetual snow, and are fully revealed only when melting has reached its maximum and the snows of the winter have not yet begun to accumulate.

Moraines. — From any commanding station overlooking Malaspina glacier, one sees that the great central area of clear, white ice is bordered on the south by a broad, dark band formed by boulders and stones. Outside of this and forming a belt concentric with it is a forest-covered area, in many places four or five miles wide. The forest grows on a moraine, which rests upon the ice of the glacier. In a general view by far the greater part of the surface of the glacier is seen to be formed of clear ice, but in crossing it one comes first to the forest and moraine-covered border, which, owing to the great obstacles it presents to travel, impresses one as being more extensive than it is in reality.

The moraines not only cover all of the outer border of the glacier, but stream off from the mountain spurs projecting into it on the north. As indicated on the accompanying map, one of these trains starting from a spur of the Samovar hills crosses the entire breadth of the glacier and joins the marginal moraine on its southern border. This long train of stones and boulders is really a highly compound medial moraine formed at the junction of the expanded extremities of the Seward and Agassiz glaciers.

All of the glaciers which feed the great piedmont ice sheet are above the snow line, and the débris they carry only appears at the surface after

the ice descends to the region where the annual waste is in excess of the annual supply. The stones and dirt previously contained in the glacier are then concentrated at the surface, owing to the melting of the ice. This is the history of all of the moraines on the glacier. They are formed of the débris brought out of the mountains by the tributary alpine glaciers and concentrated at the surface by reason of the melting of the ice.

Malaspina glacier in retreating has left irregular hillocks of coarse débris which are now densely forest-covered. These deposits do not form a continuous terminal moraine, however, but a series of irregular ridges and hills having a somewhat common trend. They indicate a slow general retreat without prolonged halts. The heaps of débris left as the ice front retreated have a general parallelism with the present margin of the glacier and are pitted with lake basins, but only their higher portions are exposed above the general sheet of sand and gravel spread out by streams draining the glacier.

The blocks of stone forming the moraines now resting on the ice are of all sizes up to 20 or 30 feet in diameter, but those of large dimensions are not common. The stones are rough and angular except when composed of material like granite, which on weathering forms oval and rounded boulders of disintegration. So far as has been observed, very few of the stones on the glacier have polished or striated surfaces. The material of which the moraines are composed is of many kinds, but individual ridges frequently consist of fragments of the same variety of rock, the special kind in each case depending on the source of the thread in the great ice current which brought the fragments from the mountains.

In many instances, particularly near the outer border of the ice sheet, there are large quantities of tenacious clay, filled with angular stones, which is so soft, especially during heavy rains, that one may sink waist deep in the treacherous mass. Sometimes blocks of stone a foot or more square float on the liquid mud and lure the unwary traveler to disaster.

On the eastern margin of the ice sheet adjacent to Yakutat bay, where the frontal slope is low, there are broad deposits of sand and well-rounded gravel which has been spread out over the ice. On the extreme margin of the glacier this deposit merges with hillocks and irregular knolls of the same kind of material, some of which rise a hundred feet above the nearest exposure of ice and are clothed with dense forests. The débris is so abundant and the ice ends in such a low slope that it is frequently im-

possible to determine where the glacier actually terminates. The water-worn material here referred to as resting on the glacier has been brought out of tunnels in the ice, as will be noticed further on.

Surface of the Fringing Moraines. — A peculiar and interesting feature of the moraine on the stagnant border of Malaspina glacier is furnished by the lakelets that occur everywhere upon it. These are found in great numbers both in the forest-covered moraine and in the outer border of the barren moraine. They are usually rudely circular, and have steep walls of dirty ice which slope toward the water at high angles, but are undercut at the bottom, so that the basins in vertical cross-section have something of an hour-glass form. The walls are frequently from 50 to 100 feet high, with a slope of 40 to 50 degrees, and sometimes are nearly perpendicular. Near the water's edge the banks are undercut so as to leave a ridge projecting over the water. The upper edge of the walls is formed of the sheet of débris which covers the glacier, and the melting of the ice beneath causes this material to roll and slide down the ice slopes and plunge into the waters below. The lakes are usually less than 100 feet in diameter, but larger ones are by no means uncommon, several being observed which were 150 or 200 yards across. Their waters are always turbid, owing to the mud which is carried into them by small avalanches and by the rills that trickle from their sides. The rattle of stones falling into them is frequently heard while traveling over the glacier, and is especially noticeable on warm days, when the ice is melting rapidly, but is even more marked during heavy rains. The crater-like walls inclosing the lakes are seldom of uniform height, but frequently rise into pinnacles. Between the pinnacles there are occasionally low saddles, through which in some instances the lakes overflow. Frequently there are two low saddles nearly opposite to each other, which suggests that the lakes were formed by the widening of crevasses. The stones and dirt which fall into them, owing to the melting of the walls, gradually fill their bottoms. Instances are numerous where the waters have escaped through crevasses or openings in the bottom of the basin, leaving an exceedingly rough depression, with a heavy deposit of débris at the bottom.

As the general surface of the glacier is lowered by melting, the partially filled holes gradually disappear, and their floors, owing to the deep accumulation of débris on them, which protects the ice from melting, become elevated above the surrounding surface, in the same manner that glacial tables are formed. The débris covering these elevations slides down

their sides as melting progresses; and finally a rugged pyramid of ice, covered with a thin coating of débris, occupies the place of the former lake. These pyramids frequently have a height of 60 or 80 feet, and are sometimes nearly conical in shape. They resemble "sand cones," but are of much greater size and are sheathed with coarser débris. The sand cones

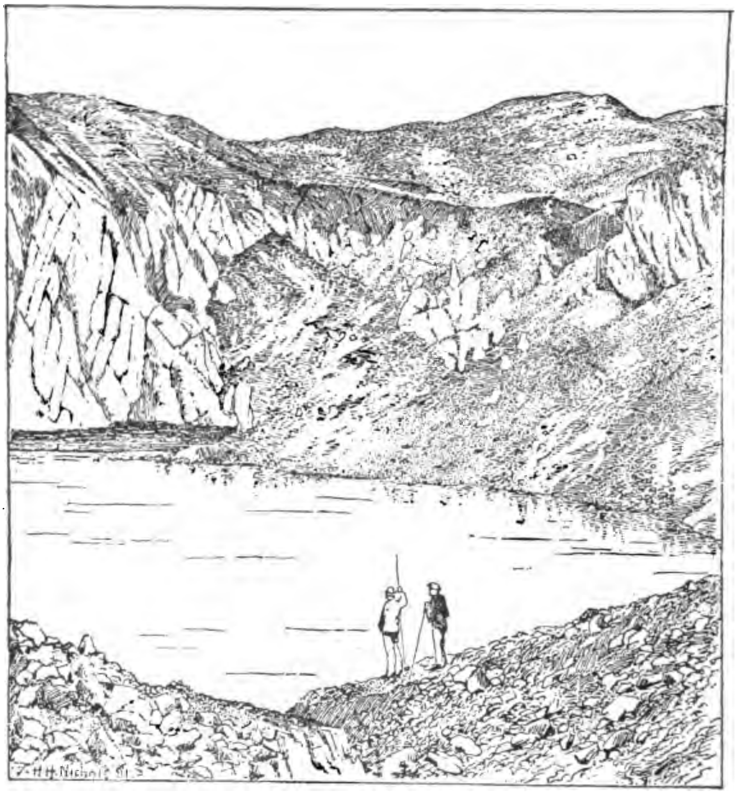


FIG. 9.—LAKELET ON MALASPINA GLACIER, ALASKA.

are usually, if not always, formed and melted away during a single season, while the débris pyramids require several seasons for their cycle of change.

Like the lakelets to which they owe their origin, the débris pyramids are confined to the stagnant portions of the glacier and play an important part in the breaking up and comminution of the material forming the marginal moraines. Owing to the sliding of the boulders and stones into the lakelets and their subsequent fall from the sides of the pyramids, they

are broken and crushed, so that the outer portion of the glacier, where the process has been going on longest, is covered with finer débris and contains more clay and sand than the inner portions.

Just how the holes containing glacial lakelets originate it is difficult to say, but their formation seems to be initiated, as already suggested, by the melting back of the sides of crevasses. Breaks in the general sheet of débris covering the glacier expose the ice beneath to the action of the sun and rain, which causes it to melt and the crevasses to broaden. The openings become partially filled with water, and lakelets are formed. The waves wash the débris from the ice about the margin of the lakelets, thus exposing it to the direct attack of the water, which melts it more rapidly than higher portions of the slopes are melted by the sun and rain. It is in this manner that the characteristic hour-glass form of the basins originates. The lakelets are confined to the outer or stagnant portion of the glacier, for the reason that motion in the ice would produce crevasses through which the water would escape. Where glacial lakelets occur in great numbers it is evident that the ice must be nearly or quite stationary, otherwise the basins could not exist for a series of years. The lakelets and the pyramids resulting from them are the most characteristic features of the outer border of the glacier. The number of each must be many thousand. They occur not only in the outer portion of the barren moraine, but also throughout the forest-covered area still nearer the outer margin of the glacier. Large quantities of trees and bushes fall into them with the débris that slides from their sides, and tree trunks, roots, and soil thus become buried in the moraines.

Forests on the Moraines.— The outer and consequently older portions of the fringing moraines are covered with vegetation, which in places, particularly near the outer margin of the belt, has all the characteristics of old forests. It consists principally of spruce, alder, and cottonwood trees, and a great variety of shrubs, bushes, and ferns. In many places the ice beneath the dense forest is not less than a thousand feet thick. The vegetation is confined principally to the border of the Seward lobe. Near Yahtse river the belt is five miles broad, but decreases toward the east and is absent at the Sitkagi bluffs, where the glacier is being eaten away by the sea. It is only on the stagnant borders of the ice sheet that forests occur. Both glacial lakelets and forests on the moraines are absent where the ice has motion. The forest-covered portion is, by estimate, between 20 and 25 square miles in area.

Character of the Outer Margin.—The southern margin of Malaspina glacier, between the Yahtse and Point Manby, is abrupt, and forms a bluff that varies in height from 140 to 300 feet or more. The bluff is so steep in most places and is so heavily encumbered with fallen trees and boulders that it is with difficulty one can climb it. Often the trouble in ascending is increased by landslides, which have piled the superficial material in confused heaps, and in other instances the melting of the ice beneath the vegetation has left concealed pitfalls into which one may drop without warning. The bluff formed by the margin of the glacier, when not washed by the sea, is boldest and steepest where the covering of vegetation is most dense. Where the covering consists of stones and dirt without vegetation, however, the margin may still be bold. This is illustrated between the mouth of the Yahtse and Icy cape, where the ice is concealed beneath a general sheet of débris, but has a bold convex margin which rises abruptly from the desolate, torrent-swept waste at its base.

When the glacier meets the sea the ice is cut away at the water-level, and blocks fall from above, leaving perpendicular cliffs of clear ice. At Icy cape there is a bold headland of this nature from which bergs are continually falling with a thunderous roar that may be heard fully twenty miles away. On the crest of the cliffs of clear blue ice there is a dark band formed by the edge of the sheet of débris covering the glacier, and showing that the moraine which blackens its surface along its outer margin is entirely superficial. At Sitkagi bluffs the glacier is again washed by the sea, but the base of the ice is there just above the water-level and recession is slow. The bluffs are heavily covered with stones and dirt, and icebergs do not form.

At the heads of the gorges in the margin of the glacier leading to the mouths of tunnels, the dirt-covered ice forms bold cliffs which are most precipitous at the heads of the reëntrant angles. The eastern margin of the ice sheet facing Yakutat bay is low, and covered to a large extent with water-worn débris. The ridges on the glacier formed by moraines are there at right angles to the margin of the ice, and are bare of vegetation. The reason for the exceptionally low slope of the eastern margin of the ice sheet seems to be that the current in the ice is there eastward, and the glacier is melting back without leaving a stagnant border.

Marginal Lakes.—The water bodies here referred to are called *marginal lakes*, for the reason that they are peculiar to the margins of

MALASPINA GLACIER, ALASKA, LOOKING EAST FROM NEAR THE SUMMIT OF THE CHAIX HILLS.

glaciers. Where rocks border an ice field or project through it they become heated, especially on southern exposures, and, radiating heat to the adjacent ice, cause it to melt. A depression is thus formed along the margin of the ice which becomes a line of drainage. Water flowing through such a channel accelerates the melting of the ice, at least until a heavy coating of débris has accumulated. When a steep mountain spur projects into an ice field, the lines of drainage on each side converge and frequently unite at its extremity, forming a lake, from which the water usually escapes through a tunnel in the ice. Typical instances of lakes of this character occur at Terrace point, at the south end of the Hitchcock range, and again about the base of the Chaix hills.

When a stream flows along the side of a glacier a movement in the ice or the sliding of stones and dirt from its surface sometimes obstructs the drainage and causes the formation of another variety of marginal lakes. In such instances the imprisoned waters usually rise until they can find an outlet across the barrier, and then cut a channel through it.

A glacier in flowing past the base of a mountain frequently obstructs the drainage of lateral valleys, and causes lakes to form. These usually find outlets, as in the case of lakes at the end of mountain spurs, through a subglacial or englacial tunnel, and are filled or emptied according as the tunnel through which the waters escape affords free drainage, or is obstructed. Several examples of this variety of marginal lakes occur on the west and south sides of the Chaix hills. They correspond in the mode of their formation with the well-known Merjelen lake of Switzerland.

Other variations in the manner in which glaciers obstruct drainage might be enumerated, but those mentioned cover all of the examples thus far observed about Malaspina glacier. The conditions which lead to the formation of the marginal lakes are unstable, and the records which the lakes leave in the form of terraces, deltas, etc., are consequently irregular. When streams flow into one of these lakes, deltas and horizontally stratified lake beds are formed as in ordinary water bodies ; but, as the lakes are subject to many fluctuations, the elevations at which the records are made are continually changing, and in instances like those about Malaspina glacier, where the retaining ice body is constantly diminishing, may occupy a wide vertical interval.

Drainage begins on the southeast side of Chaix hills at Moore's nunatak, where, during the time of our visit, there were two small lakes,

walled in on nearly all sides by the moraine-covered ice of Malaspina glacier. The water filling these basins comes principally from the high ice fall at the north, where the glacier descends over a projecting spur running east from Moore's nunatak. The water escaped from the first lake across a confused mass of débris which had slid from the ice bluff bordering the stream, and formed a temporary dam. Below the dam the water soon disappeared beneath deeply crevassed and heavily moraine-covered ice, and came to light once more at the mouth of a tunnel about a mile to the southwest. The second lake, at the time of our visit, had almost disappeared, but its former extent was plainly marked by a barren sand-flat, many acres in extent, and by terraces along its western border. The lake occupied a small embayment in the hills, the outlet of which had been closed by the ice flowing past it. Below the second lake the stream flows along the base of densely wooded knolls, and has a steep, moraine-covered bluff of ice for its left bank. About a mile below, it turns a sharp projection of rocks and cuts deeply into its left bank, which stands as an overhanging bluff of dirty ice, over 100 feet high. The stream then flows nearly due west for some three miles to Crater lake. On its right bank is a terrace about 150 feet high, which skirts the base of the Chaix hills, and marks the position of the stream at a former stage. The terrace is about 100 yards broad, and above it are two other terraces on the mountain slope, one at an elevation of 50 feet, and the other at 75 feet, above the broad terrace. The upper terraces were only observed at one locality, and were probably due to deposits formed in a marginal lake at the end of a mountain spur.

The terraces left by streams flowing between a moraine-covered glacier and a precipitous mountain slope are peculiar and readily distinguishable from other similar topographic features. The channels become filled principally with débris which slides down the bank of ice. This material is angular and unassorted, but when it is brought within the reach of flowing waters soon becomes rounded and worn. On the margin of the channel, adjacent to the glacier, there is usually a heavy deposit of unassorted débris, which rests partly upon the ice and forms the actual border of the stream. When the glacier is lowered by melting, the stream abandons its former channel and repeats the process of terrace-building at a lower level. The material forming the terrace at the base of Chaix hills is largely composed of blue clay filled with both angular and rounded stones and boulders, but its elevated border is almost entirely of angular débris. The drainage from the mountain slope above the terrace is

obstructed by the elevated border referred to, and swamps and lagoons have formed back of it. In the material forming the terraces there are many tree trunks, and growing upon its surface there is a forest of large spruce trees.

At the extreme southern end of the Chaix hills the drainage from the northeast, which we have been tracing, joins another stream from the northwest and forms Lake Castani. This lake, like the one at Terrace point, is at the south end of a precipitous mountain ridge projecting into the glacier, and drains through a tunnel in the ice. The stream flowing from it is known as the Yahtse, and flows for six or eight miles beneath the ice before emerging at its southern margin. Large quantities of both coarse and fine material are being carried into Lake Castani by tributary streams, and are there deposited as deltas and lake beds. When the lake is drained, as sometimes happens, vast quantities of this material must be carried into the tunnel through which the waters escape.

On the west side of Chaix hills are several other marginal lakes of the same general character as those just described. The one next northwest of Lake Castani occupies a long, narrow valley between two outstanding mountain ridges, and is retained by the glacier which blocks the end of the recess thus formed. This lake was clear of ice July, 1891, and of a dark blue color, showing that it received little drainage from the glacier. Other lakes on the northwest side of the Chaix hills are of a similar nature, and during my visit were heavily blocked with floating ice. On the north side of Chaix hills there are other small water bodies occupying embayments, and retained by the glacier which flows past their entrances. The water from all these lakes escapes through tunnels.

The lakes to which attention has been directed are especially interesting, as they illustrate one phase of deposition depending upon glaciation, and suggest that a great ice sheet like that which formerly covered New England very likely gave origin to marginal lakes, the records of which should be found on steep mountain slopes.

Drainage. — The drainage of the Malaspina glacier is essentially englacial or subglacial. There is no surface drainage excepting in a few localities, principally on its northern border, where there is a slight surface slope, but even in such places the streams are short and soon plunge into a crevasse or a moulin and join the drainage beneath.

On the lower portions of the alpine glaciers, tributary to the main ice sheet, there are sometimes small streams coursing along in ice channels,

but these are short-lived. On the borders of the tributary glaciers there are frequently important streams flowing between the ice and the adjacent mountain slope, but when these come down to the Malaspina glacier they flow into tunnels and are lost to view.

Along the southern margin of the glacier, between the Yahtse and Point Manby, there are hundreds of streams which pour out of the escarpment formed by the border of the glacier, or rise like great fountains from the gravel and boulders accumulated at its base. All of these are brown and heavy with sediment and overloaded with boulders and stones. The largest and most remarkable of these springs is the one indicated on the accompanying map as Fountain stream. This comes to the surface through a rudely circular opening, nearly 100 feet in diameter, surrounded in part by ice. Owing to the pressure to which the waters are subjected, they boil up violently, and are thrown into the air to the height of 12 or 15 feet, and send jets of spray several feet higher. The waters are brown with sediment, and rush seaward with great rapidity, forming a roaring stream fully 200 feet broad, which soon divides into many branches, and is spreading a sheet of gravel and sand right and left into the adjacent forest. Where Fountain stream rises the face of the glacier is steep and covered with huge boulders, many of which are too large for the waters to move. The finer material has been washed away, however, and a slight recession in the face of the ice bluff has resulted. The largest stream draining the glacier is the Yahtse. This river, as already stated, rises in two principal branches at the base of the Chaix hills, and flowing through a tunnel some six or eight miles long, emerges at the border of the glacier as a swift brown flood fully 100 feet across and 15 or 20 feet deep. The stream, after its subglacial course, spreads out into many branches, and is building up an alluvial fan which has invaded and buried several hundred acres of forest.

In traversing the coast from the Yahtse to Yakutat bay, we crossed a large number of streams which drain the ice fields of the north, some of which were large enough to be classed as rivers. When the streams, on flowing away from the glacier, are large, they divide into many branches, as do the Yahtse and Fountain, and enter the sea by several mouths. When the streams are small, however, they usually unite to form large rivers before entering the ocean. The Yahtse and Fountain, as we have seen, are examples of the first, while Manby and Yahna streams are examples of the second class. Manby stream rises in hundreds of small springs along the margin of the glacier, which flow across a desolate,

torrent-swept area, and unite just before reaching the ocean into one broad, swift flood of muddy water, much too deep for one to wade.

On the border of the glacier facing Yakutat bay, however, the drainage is different. The flow of the ice is there eastward, although the margin is probably stagnant, and instead of forming a bold, continuous escarpment, ends irregularly and with a low frontal slope. The principal streams on the eastern margin in 1891, were the Osar, Kame, and Kwik. Each of these issues from a tunnel and flows for some distance between walls of ice. Of the three streams mentioned, the most interesting is the Kame, which issues as a swift brown flood partially choked with broken ice from the mouth of a tunnel, and flows for half a mile in an open cut between precipitous walls of dirty ice 80 to 100 feet high. This is the longest open drainage channel that I have yet seen in the ice. It is about 50 feet broad where the stream rushes from the glacier, but soon widens to several times this breadth. Its bottom is covered with rounded gravel and sand, and along its sides are sand-flats and terraces of gravel resting upon ice. The swift, muddy current was dotted with small bergs stranded here and there in the center of the stream, showing that the water was shallow. Evidently the stream has a long subglacial course, and carries with it large quantities of stones, which are rounded as in ordinary rivers. Gravel and sand are being rapidly deposited in the ice channel through which it flows after emerging from its tunnel. Broad sand-flats are being spread out in the lakes and swamps two or three miles to the east. The stream is some four or five miles in length, and near Yakutat bay meanders over a barren area perhaps a mile broad. I have called it Kame stream because of a ridge of gravel running parallel with it, which was deposited during a former stage, when the waters flowed about 100 feet higher than now and built up a long ridge of gravel on the ice which has all the characteristics of the kames in New England. In the more definite classification of glacial sediments now adopted, this would more properly be called an osar.

Near the shore of Yakutat bay, the streams from the glacier spread out in lagoons and sand-flats, where much of the finer portion of the material they carry is deposited. Sometimes this débris is spread out above the ice, and forms level terraces of fine sand and mud which become prominent as the glacier wastes away.

Osars. — The drainage of the glacier has not been investigated as fully as its importance demands, but the observations already made seem

to warrant certain conclusions in reference to deposits made within the glacier by subglacial or englacial streams.

When the streams from the north reach the glacier they invariably flow into tunnels and disappear from view. The entrances to the tunnels are frequently high arches, and the streams flowing into them carry along great quantities of gravel and sand. About the southern and eastern borders of the glacier, where the streams emerge, the arches of the tunnels are low, owing principally to the accumulation of débris which obstructs their discharge. In some instances, as at the head of Fountain stream, the accumulation of débris is so great that the water rises through a vertical shaft in order to reach the surface, and rushes upward under great pressure. The streams flowing from the glacier bring out large quantities of well-rounded sand and gravel, much of which is immediately deposited in alluvial cones. This much of the work of subglacial streams is open to view, and enables one to infer what takes place within the tunnels, and to analyze, to some extent, the processes of stream deposition beneath glacial ice.

The streams issuing from the ice are overloaded, and besides, on emerging, frequently receive large quantities of coarse débris from the adjacent moraine-covered ice cliffs. The streams at once deposit the coarser portion of their loads, thus building up their channels and obstructing the outlets of the tunnels. The blocking of the tunnels must cause the subglacial streams to lose force and deposit sand and gravel on the bottom of their channels ; this causes the water to flow at higher levels, and, coming in contact with the roofs of the tunnels, enlarges them upwards ; this in turn gives room for additional deposits within the ice as the alluvial cones at the extremities of the tunnels grow in height. In this way narrow ridges of gravel and sand, having, perhaps, some stratification due to periodic variations in the volume of the streams, may be formed within the ice. When the glacier melts, the gravel ridges contained within it will be exposed at the surface, and as the supporting walls melt away, the gravel at the top of the ridge will tend to slide down so as to give the deposit a pseudo-anticlinal structure. Ridges of gravel deposited in tunnels beneath the moraine-covered portion of the Malaspina glacier would have boulders dropped upon them as the ice melts, but where the glacier is free from surface débris there would be no angular material left upon the ridges when the ice finally disappeared. Such a system of deposition as is sketched above would result in the formation of narrow, winding ridges of cross-bedded sand and gravel, corresponding,

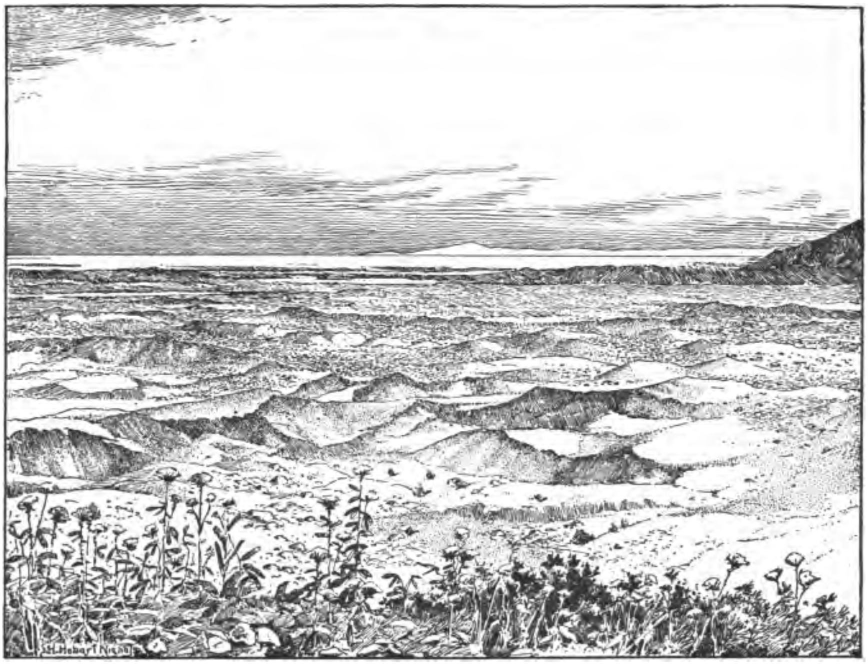


FIG. A.—MORAINE-COVERED BORDER OF MALASPINA GLACIER, FROM BLOSSOM ISLAND.

(Drawn from a Photograph.)

FIG. B.—ENTRANCE TO TUNNEL IN MALASPINA GLACIER.

(Drawn from a Photograph.)

seemingly, in every way to the osars of many glaciated regions. The process of subglacial deposition pertains especially to stagnant ice sheets of the Malaspina type, which are wasting away. In an advancing glacier it is evident that the conditions would be different, and subglacial erosion might take place instead of subglacial deposition.

Alluvial Cones. — Below the outlets of the tunnels through which Malaspina glacier is drained, there are immense deposits of boulders, gravel, sand, and mud which have the form of segments of low cones. These deposits are of the nature of the "alluvial cones" or "alluvial fans" so common at the bases of mountains in arid regions, and are also related to the "cones of dejection," deposited by torrents, and to the subaërial portion of the deltas of swift streams. As deposits of this nature have not been satisfactorily classified, I shall, for the present, call them "alluvial cones."

As stated in speaking of osars, the streams issuing from tunnels in Malaspina glacier at once begin to deposit. The larger boulders and stones are first dropped, while gravel, sand, and silt are carried farther and deposited in the order of their coarseness. The deposits originating in this way have a conical form, the apex of each cone being at the mouth of a tunnel. As the apexes of the cones are raised by the deposition of coarse material, their peripheries expand in all directions, and, as the region is densely forest-covered, great quantities of trees become buried beneath them. As the ice at the head of an alluvial cone recedes, the alluvial deposit follows it by deposition on the up-stream side. The growth of the alluvial cones will continue so long as the glacier continues to retreat, or until the streams which flow over them have their subglacial courses changed. The material of the alluvial cones is as heterogeneous as the material forming the moraines on the border of the glacier about which they form, but the greater, and practically the entire, accumulation is more or less rounded and waterworn. Cross stratification characterizes the deposits throughout, and on the surface of many of the cones and probably in their interior, also, there are large quantities of broken tree trunks and branches. The coarse deposits first laid down on a growing alluvial cone are buried beneath later deposits of finer material in such a way that a somewhat regular stratification may result. A deep section of one of these deposits should show a gradual change from fine material at the top to coarse stones and subangular boulders at the bottom. Their outer borders are of fine sand and mud, and when the distance of the

ocean is sufficient, the streams flowing from them deposit large quantities of silt on their flood plains. The very finest of the glacial mud is delivered to the ocean and discolors its water for many miles from land.

The formation of alluvial cones about the border of a stagnant ice sheet and the deposition of ridges of gravel within it, have an intimate connection, and are, in fact, but phases of a single process. The growth of an alluvial cone tends to obstruct the mouth of the tunnel through which its feeding stream discharges; this causes the stream to deposit within the tunnel; this again raises the stream and allows it to build its alluvial cone still higher. In the case of Malaspina glacier, where this process has been observed, the ice sheet is stagnant, at least on its border, and is retreating. The ground on which it rests is low, but is thought to be slightly higher on the southern margin of the glacier than under its central portion. The best development of alluvial cones and osars would be expected in a stagnant ice sheet resting on a gently inclined surface, with high lands on the upper border from which abundant débris could be derived. These ideal conditions are nearly reached in the example described.

Glacial and Ocean Records. — Much has been written concerning the character of the deposits made by glaciers when they meet the ocean, but so far as can be judged from the conditions observed about the borders of Malaspina ice sheet, the sea is much more powerful than the ice. Where the two unite their action, the sea leaves the more conspicuous records. The waters are active and aggressive, while the glacier is passive. Where the glacier enters the ocean its records are at once modified and to a great extent obliterated. The presence of large boulders in marine sediments or in gravels and sands along the coast is about all the evidence of glacial action that can be expected under the conditions referred to. Where the swift streams from the Malaspina glacier enter the ocean, the supremacy of the waves, tides, and currents is even more marked. The streams are immediately turned aside by the accumulation of sandbars across their mouths, and nothing of the nature of stream-worn channels beneath the level of the ocean can exist. All of the deposits along the immediate shore between the Yahtse and Yakutat bay have the characteristic topographic features resulting from the action of waves and currents, and do not even suggest the proximity of a great glacier.

Recent Advance. — On the eastern margin of Malaspina glacier, about four miles north of Point Manby, there is a locality where the ice

has recently advanced into the dense forest and cut scores of great spruce trees short off and piled them in confused heaps. After this advance the ice retreated, leaving the surface strewn with irregular heaps of boulders and stones, and enclosing many basins, which, at the time of our visit, were full of water to the brim. The glacier, during its advance, ploughed up a ridge of blue clay in front of it, thus revealing, in a very satisfactory manner, the character of the strata on which it rests. The clay is thickly charged with sea-shells of living species, proving that the glacier, during its former great advance, probably extended to the ocean, and that a rise of the land has subsequently occurred. This is in harmony with many other observations which show that the coast adjacent to Malaspina glacier is now rising. The blue color of the subglacial strata is in marked contrast with the browns and yellows of the moraines left on its surface by the retreating ice, which, in common with the fringing moraines still resting on the glacier, show considerable weathering. Among the shells collected in the subglacial clay, Dr. W. H. Dall has identified the following:

Cardium gronlandicum, Gronl.
Cardium islandicum, L.
Kennerlia grandis, Dall.
Leda fossa, Baird.
Macoma sabulosa, Spengler.

Similar shells, all of living species, were previously found at an elevation of 5000 feet on the crest of a fault scarp at Pinnacle pass, showing that recent elevations of land, much greater than the one recorded in the marine clay just noticed, have taken place. In fact there are several indications that the coast in the vicinity has been rising, and that the same process is still continuing.

Subsoil Ice.[1]

On several occasions while traveling in central and northern Alaska, I found, by removing a few inches of the moss which generally covers the ground, that the subsoil was solidly frozen. This occurrence was especially striking on summer days when the temperature of the air in the shade was frequently between 90° and 100° of the Fahrenheit scale.

[1] Observations on the subsoil ice of Alaska by the present writer, together with references to a number of previously published papers on the same subject, may be found in the Bulletin of the Geological Society of America, vol. 1, pp. 125–133.

Along the Yukon, from its mouth to near its source, one may frequently see strata of clear ice, or more frequently of black, dirt-stained ice and frozen gravel several feet thick, in the freshly cut banks of the stream. In general, throughout the low-lying portions of central Alaska, subsoil ice exists at a depth of but a few inches beneath the forest-covered surface. The maximum thickness of this permanently frozen layer is not known, but in a few instances of which I have authentic information, it has been penetrated to a depth of 25 feet without reaching the bottom.

Explorations conducted by Lieut. J. C. Cantwell,[1] of the U. S. Revenue Marine service, along the Kowak river, which flows into Kotzebue sound, about 260 miles north of the mouth of the Yukon, and just within the Arctic circle, have shown that a layer of subsoil ice from 100 to 200 feet thick has there been cut into by the streams so as to leave steep bluffs of solid ice along their borders. The ice covers the land like a stratum of rock, and has been dissected by stream erosion in much the same manner that river channels are corraded in other regions. Above the ice there is a thin covering of rich black soil supporting a growth of mosses, grasses, and trees. Instructive illustrations of the Kowak river flowing between precipitous, cañon-like walls of ice are presented in the report just referred to.

One of the most striking exposures of subsoil ice in Alaska, and one that has been described by many travelers, exists on the shore of Eschscholtz bay at the head of Kotzebue sound. The ice there forms a bold bluff, and has been estimated to be from 150 to 300 feet thick. It is covered with rich humus, on which grasses grow luxuriantly. In this instance, as in several other similar examples that are known, the ice contains the bones of the mammoth and other large animals that are now extinct. The soil which accumulates as the ice melts, owing to the concentration at the surface of the impurities it contains, has a strong odor of decaying animal matter. We are thus assured that the subsoil ice, in certain instances, and probably over extensive areas, was formed at a time so remote that the animals then inhabiting the country in great numbers have since become extinct.

The ice in the banks of the lower Yukon, and in the vicinity of Kotzebue sound, is a part of a vast sheet of frozen subsoil that underlies large portions of the low, marshy region fringing the shores of Bering

[1] "A Narrative Account of the Exploration of the Kowak River, Alaska," in Report of the Cruise of the Revenue Marine Steamer *Corwin*, in the Arctic Ocean, in the year 1885, by Capt. M. A. Healy, Treasury Department, Washington, D.C., 1887.

sea and the Arctic ocean. This *tundra*, as it is termed, covers many thousands of square miles. It is bright with mosses and a profusion of low, flowering plants during the short Arctic summer, but beneath its luxuriant carpet of verdure the ground is always frozen.

Still more extensive tundras cover the low lands forming the Arctic shores of Asia, and have there been penetrated to a depth of nearly 400 feet without reaching the bottom of the subsoil ice. It is in this deposit that the complete carcasses of the mammoth and of the woolly rhinoceros are found from time to time. The fossil ivory gathered along the banks of the rivers in this Arctic region is said to be even more important as an article of commerce than the elephant tusks obtained in the jungles of Africa.

It is not probable that all of the subsoil ice of northern regions has been formed in one way. Along the flood plains and on the deltas of rivers where layers of clear ice are interbedded with sheets of frozen gravel and vegetable matter, as is frequently the case, it seems evident that the growth of the deposit is due, in some instances, to the flooding of previously frozen layers, and the freezing and subsequent burial of the sediment thus added to their surfaces. When spring freshets spread out sheets of débris over the flood plain of a river, as frequently happens when streams in high latitudes flow northward, the previously frozen soil and the ice of ponds and swamps may be buried and indefinitely preserved. During the succeeding winter the surface layer thus added would itself become frozen, and perhaps in its turn become buried beneath later deposits of the same character at intervals of one or more years.

On the tundras the luxuriant growth of vegetation that starts into life as soon as the winter's snow has disappeared, and grows rapidly during the long, hot summer days, dies below and partially decays, but becomes frozen and has its complete destruction arrested, while the dense mat of roots and stems above continues to thrive. In this way an accumulation of partially decayed vegetable matter is formed, which increases in thickness from year to year by additions to its surface. The process is similar to that by which peat bogs are formed in temperate latitudes, except that the partially decomposed vegetation becomes solidly frozen. It is in reality an example of cold storage on a grand scale. This slow accumulation in northern regions of vegetable matter, together with the bones and even complete carcasses of animals, is truly a wonderful process. Under existing climatic conditions there does not seem to be any limit to the depth such deposits may attain. The amount of carbonaceous

material already accumulated in the tundras of America and Asia must equal that of the most expensive coal field known. In view of these facts it does not seem an unreasonable suggestion that some coal seams might have originated from the vegetable matter accumulated in ancient tundras.

There is still another process by which frozen subsoil may be formed in high latitudes: this is, the effects of the cold during the long winters are not counteracted by the heat during the short summers. Under the conditions now prevailing in northern Alaska, where the mean annual temperature is below 32° Fahrenheit, the frozen layer tends to increase in thickness from year to year just as the depth of frozen soil in more temperate latitudes may increase from month to month during the winter season. During the short northern summers, especially where the ground is moss-covered, melting only extends a few inches below the surface.

Computations made by Prof. R. S. Woodward[1] have shown that the freezing of even the deepest ice stratum yet discovered in Arctic regions might have resulted in the course of a few thousand years from a mean annual temperature no lower than that prevailing in northern Alaska at the present time.

The subsoil ice described above lacks most of the characteristics of glaciers and should not be included among them. It is so closely analogous, however, to the condition reached by continental and piedmont glaciers when they become stagnant and are wasting away, that the mode of its formation needs to be understood in order that the two may not be confounded. The climatic conditions admitting of the accumulation of subsoil ice are similar, and probably identical, to those which initiate glacial periods. In times immediately preceding the formation of continental glaciers, it is possible that subsoil ice like that of the tundras may be formed over extensive regions before they become covered by a flowing ice sheet. In such an instance the frozen subsoil might become a part of a continental glacier when covered by the advancing ice. During the amelioration of climate following an ice invasion, the tundra phase might again return, so that a glacial period would be both preceded and followed by a time when the mean annual temperature would favor the existence of deeply frozen subsoil, and, at the same time, admit of the growth of luxuriant forests.

[1] Geological Society of America, Bulletin, vol. 1, pp. 131, 132.

CHAPTER VII.

GLACIERS IN THE GREENLAND REGION.

Grinnell Land.— Explorations in the extreme northeastern part of North America have been carried on principally along the navigable water ways. It is only recently that a knowledge has been gained of the vast snow fields in which the glaciers descending to the sea have their origin. The most instructive journeys that have been made on the islands to the west of Baffin's bay, Davis strait, etc., were by members of the Lady Franklin Bay expedition in 1882. Gen. A. W. Greely, in his admirable account of "Three Years of Arctic Service," describes the United States mountains in the northern part of Grinnell land, as being buried beneath névé snow, and apparently presenting much the same appearance as the desolate region to the north of Mount St. Elias, described in the preceding chapter.

The largest ice stream draining the snow fields of Grinnell land yet discovered, known as the Henrietta Nesmith glacier, flows south and terminates near Lake Hazen. The most striking feature of this great glacier, and one that seems to be characteristic of many of the ice streams of the far north, is the extremely precipitous slope in which it terminates. As shown in an illustration published by General Greely, its extremity is a nearly vertical wall of ice, perhaps 150 or 200 feet high. The main glacier is formed by the union of five independent streams, which pour down from an extensive ice cap to the north of the Garfield range and south of the United States mountains. A tributary from the west joins the main glacier about four miles above its terminus, and a second and third tributary comes in from the northeast about seven and ten miles, respectively, inland. The main glacier is separated from the lowest tributary by a rounded mountain spur, which from the station occupied by the explorer cut off the view in that direction. In all other quarters, however, the view was unobstructed, and embraced about 13 degrees of azimuth.

The descriptions and sketches published by Greely seem to show that the United States mountains are covered with a general névé field through which the higher peaks project, and that large glaciers, resembling most

nearly those of the alpine type, descend from the snow-covered uplands in various directions. The ice streams flowing southward are the best known, although but hastily examined, as explorations have been carried nearest to the mountains in that direction.

Reports by Lieut. J. B. Lockwood and Serg. D. L. Brainard[1] of explorations across Grinnell land from Archer fiord on the east to Greely fiord on the west, show that the land both to the north and south of the route followed is heavily covered with snow fields and glaciers. The region to the south, especially, is mountainous, and the higher peaks and domes alone reveal their forms above the all-pervading snow fields. From this elevated névé a vast glacier or series of more or less confluent glaciers, named "Mer de Glace Agassiz," flows northward, and, breaking into individual ice streams, send out branches, some of which become tide-water glaciers on reaching Greely fiord. The most remarkable feature of the glaciers seen by Lockwood and Brainard, as in the case of the Henrietta Nesmith glacier, is the precipitous manner in which the ice ends. The glaciers seem to terminate on the land as abruptly as do tide-water glaciers in more southern latitudes on entering the sea. The long line of ice cliffs marking the northern margin of Mer de Glace Agassiz is termed the "Chinese Wall" in the report referred to, and, as shown in sketches, when seen from the north present the appearance of a vast wall of ice trending across the country in a general east and west direction, and forming an escarpment apparently two or three hundred feet high. Rising beyond this wall of ice, and seen over its crest, are the snow fields and bald, snow-covered mountains where the great glacier has its source.

From what is known of Grinnell land it appears that the glaciers covering its more elevated portions are of the alpine type, but differ from the glaciers in the mountainous portions of more southern lands for the reason that their gathering grounds are comparatively low, and also because the snowfall is light and melting greatly retarded. The result is that glaciers of great size are formed in regions but little elevated above the sea, and that, from some combination of conditions not yet fully explained, they end abruptly in precipitous escarpments.[2]

[1] In "Report of the Proceedings of the U. S. Expedition to Lady Franklin Bay," by A. W. Greely, Washington, 1888, vol. 1, pp. 274–296.

[2] Since this book was written, Prof. T. C. Chamberlin has made a study of some of the glaciers of Greenland, and has suggested that the low angle of incidence of the sun's rays in the far north may explain the peculiar manner in which the glaciers there terminate.

The general climatic and topographic conditions characterizing Grinnell land seem to extend southward and embrace neighboring land areas, but explorers have yet to discover the limits of the glaciers in that region, and to make more critical studies of the entire glacial system of the northeastern corner of the continent.

Greenland.

While the northern shore of Greenland remains unexplored it will be impossible to determine the full extent of the land or of the ice sheet covering it. From the most reliable data available, however, it is probable that the land is about 1500 miles long from north to south, and 800 miles broad in the widest portion. As estimated by Lieut. R. E. Peary, its area is approximately 750,000 square miles, of which fully 600,000 are ice and snow covered.

The interior of Greenland is reported by the few bold explorers who have crossed it to be completely buried beneath a featureless plain of snow. This covering has reached such a depth in all of the central part that not a single mountain peak is known to break the even monotony of its surface. The snow is highest and probably deepest in the central area, and descends toward the coast, thus giving the island a convex surface. The general elevation of the central portion is from 7000 to 8000 feet, decreasing gradually toward the coast, especially to the east and west, where the glaciers, protruding like great tongues of ice from the central region, come down to the sea. The only mountain peaks that rise above the surface of the general covering of snow are within from 50 to 75 miles of the coast. These partially buried peaks rise like islands in the sea of white. They are known to the inhabitants of the coast as *nunataks;* a convenient name that has found a place in geological literature.

The depth of the nearly universal covering of snow and ice under which Greenland is buried cannot be told, as it is impossible to determine the topography of the land beneath. The best estimates that can be made place its depth at several thousand feet. In the central portion, where the covering is apparently thickest, its depth may be fully equal to the height of the surface above the sea, or about 8000 feet.

Like the névés of smaller glaciers, the surface of all the central part of the Greenland ice sheet is composed of light granular snow. This greatest of all névés in the northern hemisphere is remarkably uniform in contour and unbroken by crevasses and unscored by water courses in all

of its central area. The ice formed beneath the névé in the interior flows outward in all directions through the passes in the mountains in independent ice streams, many of which reach the ocean and form the largest tidewater glaciers known, with the exception of those in Antarctic regions. One of the grandest of these tongues of ice is the Humboldt glacier, which flows westward and discharges into Kane basin in about latitude 79° 30′. The extremity of this glacier, explored and named by Dr. Kane, forms a wall of ice that is reported to be 40 miles long and from 200 to 300 feet high above the sea. The veritable mountains of ice that break away from the partially submerged face are of astonishing dimensions, and in many instances find their way southward through Baffin's bay to the banks of Newfoundland, and endanger the safety of trans-Atlantic steamers.

At many localities about the borders of Greenland, the rough, broken extremities of glaciers similar to Humboldt glacier are known to enter the sea. The adjacent waters are crowded with bergs shed off by these tidewater glaciers, and also with floe ice originating from the freezing of sea water. In numerous instances the tide-water glaciers end at the heads of deep fiords, as in the case of many Alaskan glaciers. Again, the ice terminates on land and presents steep, broken surfaces, that are so deeply gashed and so shattered into pinnacles and spires that it is impossible to cross them. When the topography of the high lands bordering the coast is not favorable to the formation of tongue-like glaciers in deep valleys, the ice from the great interior reservoir presses outward and terminates in blue cliffs high up on rocky slopes, but melts before descending to the sea. The rocks now bordering the glaciers, and in part confining them, are in many localities rounded, smoothed, and striated, showing that in former times the ice inundations were much more extensive than at present, and reached the sea on every hand. In other localities, as recently determined by Chamberlin, the land near the west coast has never been ice-covered. A small driftless area on the shore of Ingerfield gulf is one of the most interesting discoveries made in Greenland in recent years, and shows that the previously entertained idea that during former periods of maximum glaciation the land was entirely ice-covered is incorrect.

The information now in hand concerning the Greenland ice sheet is the result of combined observations of many explorers. Space will not admit of an historical review of the slow progress that has been made in gathering information of scientific value in the far north, but the student who desires to follow up the subject will find the necessary references in

the summaries of the geological results of northern exploration indicated in the following footnote.[1]

The rough ice met with on the borders of Greenland has been described by many writers. South of about latitude 70° it presents the characteristics of the lower extremities of alpine glaciers in less remote regions. In the northern part of the continent, however, it ends in exceptionally precipitous slopes. The tongue of ice reaching seaward between bold uplands on the west coast near Disco island, in latitude 69° 30′, is a characteristic example of what may be seen at many other localities on the wild Greenland coast. This protrusion of the island ice is described by Lieutenant Peary as follows :

"Wherever the ice projects down a valley in a long tongue or stream, the edges contract and shrink away from the warmer rocks on each side having a deep cañon between, usually occupied by a glacial stream. . . . Higher up, along the unbroken portion of the dam [*i.e.* enclosing mountains], where the rocks have a southern exposure or rise much above the ice, there is apt to be a deep cañon between the ice and the rocks; the ice face, sometimes 60 feet high, pure, pale green, and flinty.[2] In another place the ice face may be so striated and discolored as to be a precise counterpart of the rock opposite, looking as if torn from it by some convulsion. The bottom of the cañon is almost invariably occupied by water. . . . Still farther up, at the very crest of the dam, the ice lies smoothly against the rocks.

"As to the features of the interior beyond the coastline, the surface of the 'ice blink' near the margin is a succession of rounded hummocks, steepest and highest on their landward sides, which are sometimes precipitous. Farther in these hummocks merge into long, flat swells, which in turn decrease in height toward the interior, until at last a flat, gently rising plain is reached, which doubtless becomes ultimately level."

The great Humboldt glacier, already referred to, presents another example of the characteristic scenery of the Greenland coast, as is shown by the following graphic description by Dr. Kane :

[1] Dr. H. Rink, "Results of the Recent Danish Explorations in Greenland with Regard to the Inland Ice (1878–1889)," in Edinburg Geol. Soc. Trans., vol. 5, 1888, pp. 286–293.

Dr. F. Nansen, "First Crossing of Greenland," vol. 1, pp. 450–510.

G. Frederick Wright, "Ice Age in North America," pp. 67–91.

Warren Upham, "The Ice Sheet of Greenland," in American Geologist, vol. 8, 1894, pp. 145–152.

James Geikie, "The Great Ice Age," 3d ed., 1894, pp. 42–61.

T. C. Chamberlin, in the Geological Journal (Chicago) for 1894–1896.

[2] American Geographical Society, Bulletin, vol. 19, 1887, p. 286.

"The trend of this glacier is a few degrees to the west of north. We followed its face eastward, edging in for the Greenland coast, about the rocky archipelago which I have named after the *Advance*. From one of these rugged islets, the nearest to the glacier which could be approached with anything like safety, I could see another island larger and closer in shore, already half covered by the encroaching face of the glacier, and great masses of ice still detaching themselves and splintering as they fell upon the portions which protruded. Repose was not the characteristic of this seemingly solid mass; every feature indicated activity, energy, movement.

"The surface seemed to follow that of the adjacent country over which it flowed. It was undulating about the horizon, but as it descended toward the sea it represented a broken plain with a general inclination of some nine degrees, still diminishing toward the foreground. Crevasses, in the distance mere wrinkles, expanded as they came nearer, and were crossed almost at right angles by long continuous lines of fracture parallel with the face of the glacier.

"These lines, too, scarcely traceable in the far distance, widened as they approached the sea, until they formed a gigantic stairway. It seemed as though the ice had lost its support below and that the mass was let down from above in a series of steps. Such an action, owing to the heat derived from the soil, the excess of surface-drainage, and the constant abrasion of the sea, must in reality take place. The indications of a great propelling agency seemed to be just commencing at the time I was observing it. These split-off lines of ice were evidently in motion, pressed on by those behind, but still widening their fissures, as if the impelling action was more energetic near the water, till at last they floated away in the form of icebergs. Long files of these detached masses could be traced slowly sailing off into the distance, their separation marked by dark parallel shadows — broad and spacious avenues near the eye, but narrowed in the perspective to mere lines. A more impressive illustration of the forces of nature can hardly be conceived. . . .

"The frozen mass before me was similar in structure to the Alpine and Norwegian ice growths. It would be foreign to the character of this book to enter into the discussion which the remark suggests; but it will be seen by the sketch, imperfect as it is, that their face presented nearly all the characteristic features of the Swiss Alps. The 'overflow,' as I have called the viscous overlapping of the surface, was more clearly marked than upon any Alpine glacier with which I am acquainted. When close

to the island rocks and looking out upon the upper table of the glacier, I was struck with the timely analogy of the batter-cake spreading itself under the ladle of the housewife, the upper surface less affected by friction, and rolling forward in consequence.

"The crevasses bore the mark of direct fracture and the more gradual action of surface drainage. The extensive watershed between their converging planes gave to the icy surface most of the hydrographic features of a river system. The ice-born rivers which divided them were margined occasionally with spires of discolored ice and generally lost themselves in the central area of the glacier before reaching its foreground. Occasionally, too, the face of the glacier was cut by vertical lines, which, as in the Alpine growths, were evidently outlets for the surface drainage. Everything was, of course, bound by solid ice when I looked at it; but the evidence of torrent-action was unequivocal, and Mr. Bonsall and Mr. Morton, at their visit of the preceding year, found both cascades and water tunnels in abundance.

"The height of this ice wall at the nearest point was about 300 feet, measured from the water's edge; and the unbroken right line of its diminishing perspective showed that this might be regarded as its constant measurement. It seemed, in fact, a great icy table-land abutting with a clean precipice against the sea. This is, indeed, characteristic of all those Arctic glaciers which issue from central reserviors, or *mers de glace*, upon the fiords or bays, and is strikingly in contrast with the dependent or hanging glaciers of the ravines, whose every line and furrow and chasm seems to indicate the movement of descent and the mechanical disturbances which have retarded it. . . .

"As the surface of the glacier receded to the south, its face seemed broken with piles of earth and rock-stained rubbish, till far back in the interior it was hidden from me by the slope of a hill. Still beyond this, however, the white blink or glare of the sky above showed its continued extension.

"It was more difficult to trace this outline to the northward on account of the immense discharges at its base. The talus of its descent from the interior, looking far off to the east, ranged from seven to fifteen degrees, so broken by the crevasses, however, as to give the effect of an inclined plane only in the distance. A few black knobs rose from the white snow like islands from the sea. The general configuration of its surface showed how it adapted itself to the inequalities of the basin-country beneath. There was every modification of hill and valley, just as upon land."

The margin of the inland ice on the east side of Greenland has been explored, especially by Nansen, and found to have the same general characteristics as on the west coast, excepting that the strip of mountainous country intervening between the sea of ice in the interior and the sea of water to the east is narrower, and the ascent steeper. Several large glaciers are known on the east coast similar in character to the Humboldt glacier, and the adjacent waters are crowded with icebergs and with floe ice.

The northern coast of Greenland, at least as far as Cape Washington, the present limit of exploration, was found by Lockwood and Brainard to be formed by bold rock headlands separated by deep valleys and wild, desolate fiords. The mountains are snow-covered, but glaciers are not a conspicuous feature of the stern landscape, and, so far as known, none of them reach the sea. The character of the coast as seen from Cape Britannia, lat. 82° 45′, is indicated in the following description by Lieutenant Lockwood:[1]

"Owing to the continued bad weather my view of the interior was mainly confined to what I saw from the two elevations recorded; and owing to their comparative lowness, the range of mountain peaks, with their universal covering of snow, merging and overlapping one another, made it very difficult to distinguish the topography at all. The interior land seemed very high and on this account the farthest that I could see could not have been very many miles removed. I could see (from Britannia and Lockwood islands) no glaciers that I could recognize as such, though from the floe, while traveling, I saw a very large one and one or two quite small. From my farthest I saw mountains to the east, perhaps twenty or thirty miles distant, and a high mountainous country doubtless exists along this coast for some distance to the south; the shore line of the fiords invariably begin at the base of steep cliffs and mountains. No land was seen to the north. There was a very noticeable abundance of snow everywhere."

The above observations on the snowy covering of the north coast of Greenland were made in May. Judging from the reports of Lieutenant Peary, who found an abundance of flowers at the farthest point reached during his overland journey, much of the land seen by Lockwood must be bare of snow in late summer.

Far to the north, as discovered by Lieutenant Peary during his first famous journey over the inland ice, the fringe of mountains bordering the

[1] "Report of the Proceedings of the U. S. Expedition to Lady Franklin Bay," vol. 1, p. 188.

coast of Greenland and intervening between the vast snow plateau of the interior and the shore line, becomes broader, and the inland ice is limited in that direction in about the same manner as on the better-known portions of the coast to the southward. The termination of the inland ice before reaching the northern border of the land is a significant fact, which, taken in connection with the unglaciated condition of northern Alaska, suggests that possibly the north end of Greenland was free of ice even during the glacial period.

The combined observations of many explorers show that the great reservoir of snow and ice covering central Greenland, and supplied solely from the atmosphere, overflows in all directions through passes in the bordering mountains so as to form separate ice tongues, but does not enter the sea bodily, as one might say, on any considerable portion of its boundary. In this respect the continental glacier of the northern hemisphere differs from the similar ice body in Antarctic regions, which for a large part of its periphery extends out into the sea, and forms continuous ice cliffs several hundred miles long. Two phases in the existence of continental glaciers are thus illustrated. The one at the north is apparently receding and contracting its boundaries, while the one at the south is yet in its full vigor, and is possibly still increasing.

Thanks to the daring and zeal of a few explorers who have traversed the interior of Greenland, we know what the surface of a continental glacier is like, and are enabled to picture with considerable confidence the character of large portions of North America, now thickly peopled, as it existed during the height of the glacial period.

The first successful attempt to pass beyond the rugged borders of Greenland and travel on the snow surface of the interior, was made by the celebrated Swedish navigator, Baron Nordenskiold, in 1883. Leaving the west coast a little to the south of Disco bay, he traveled inland for eighteen days over a continuous snow-covered ice field which presented the characteristic features of the névé of Alpine glaciers, and rose gradually higher and higher the farther he proceeded. The region of nunataks was passed and a bold advance made over the clear unbroken surface of the inland ice which stretched away to the horizon as a boundless sea of unbroken snow. About the only conspicuous details of the surface were channels in which clear, swift streams coursed along between walls of ice. These streams were short, however, as they soon plunged into crevasses or moulins and disappeared to join the general subglacial drainage. The murmur of waters far below the surface told of streams flowing in icy

caverns beneath. We now know that these features pertain to the outer border of the ice sheet, extending, it is true, some distance inland beyond the fringe of nunataks, but are wanting over the greater part of the central region.

At the end of his inland journey Nordenskiold reached a locality about 73 miles from the coast and an elevation of 5000 feet. He then sent his two Lap companions forward on *ski*, or Norwegian snow-shoes, for a distance, it is estimated, of approximately 65 miles, or 138 miles from the starting point on the coast. The elevation at the farthest point reached is reported as being 5850 feet above the sea. To the eastward the surface still continued to rise, showing that the summit of the ice sheet was not gained. Nansen[1] has given reasons for concluding that the distance traversed by the Lapps after leaving the main party was overestimated, and that in reality the farthest point reached was but 118 miles inland.

The explorations on the inland ice made by Nordenskiold decided once for all that the previously entertained hypothesis in reference to the presence of an area in the interior of Greenland free from ice and perhaps inhabited is untenable.

In 1888, Lieut. R. E. Peary, who has since made three remarkable journeys on the inland ice of northern Greenland, made a reconnoissance in company with Christian Maigaara, a Danish officer in the Greenland service, to the east of Disco bay, and some 75 or 100 miles north of the route followed by Nordenskiold. During this reconnoissance Peary advanced about 100 miles from the coast and reached an elevation of 7525 feet on the unbroken surface of the inland ice.

Important as was the first venture that Peary made into the unexplored interior of Greenland, it has been far surpassed both by Nansen and by Peary himself in subsequent years.

Dr. Fridtjof Nansen, the most intrepid of Arctic explorers, with four companions, crossed Greenland from east to west in 1888, between latitudes 64° 10′ and 64° 15′. The width of the ice was there found to be 275 miles. Where the line of march began the ice descended to the sea and formed a tide-water glacier, but on the west it did not reach within about 14 miles of the head of Ameralik fiord, or 70 miles from the outer coastline. The highest position of the vast convex covering of ice under which the land is buried was 8920 feet. This elevation was reached at a distance of 112 miles from the east coast. The gain in elevation for the

[1] "The First Crossing of Greenland" (Longmans & Co., London, 1890), vol. 2, p. 468.

first 15 miles was 220 feet per mile, and thence to the summit 38 feet per mile. As the explorers proceeded westward from the summit the descent was still more gentle, and for fully 100 miles averaged about 25 feet per mile, a slope which no eye could distinguish from a perfect plain. A cross profile of the inland ice was thus obtained, which shows a moderate descent towards the ocean on either hand, with a broad, gently convex central portion, and illustrates the form assumed by an ice sheet as the result of accumulation at the surface and an outflow towards the margin.

The highly instructive journeys made by Peary in 1892, and repeated in part in 1894 and still again in 1895, northeastward from Inglefield gulf on the west coast, in about lat. 77° 30′, confirmed the conclusions reached during the previous explorations referred to in respect to the character of the Greenland ice sheet, and seemed to define its northern boundary, at least in a general way. In the far north the coast exhibits the same rugged character as at the south. The border of the inland ice is broken by nunataks, but the central part forms a vast plain of snow over which one may travel with dog-sleds and snow-shoes for hundreds of miles in a continuous line without meeting serious obstructions. So far as the topography is concerned it is only near the outer margin, where the ice flows between rugged highlands and mountains tops project above its surface, that serious difficulties to travel are met with. The highest point reached on the broad, gently convex surface of the ice at the north was about 8000 feet.

The principal lesson of geological interest learned from the study of the continental glaciers covering Greenland is that such glaciers may originate on land that is not mountainous and not elevated above the sea, and in regions where the snowfall is not excessive.

Many of the hypotheses advanced to account for the previous existence of glaciers over northeastern North America and over northwestern Europe might be tested in the Greenland region at the present day, and many of them, if so tested, it is safe to say, would be found wanting. It is evident that the more familiar we become with existing glaciers and with the climatic and topographic conditions on which they depend, including a study of the currents and temperatures of the adjacent sea, the better able we shall be to interpret the records left by ancient glaciers and to restore in fancy the condition of large portions of the earth now thickly inhabited when covered by former ice sheets.

Our knowledge of the glaciers of Greenland has been greatly extended by observations made by Prof. T. C. Chamberlin in the summer of 1894,

while connected with the second Peary relief expedition. The records of the studies then made were not available when the book now before you was written, although in revising it several references to them have been introduced.

A condensed account was given by Chamberlin of his observations in Greenland in the form of a presidential address before the Geological Society of America, at Baltimore, in December, 1894, and subsequently printed in the bulletin of the Society.[1] A much more extended record has since been published in the Journal of Geology.[2] These reports contain a critical and detailed account of glacial phenomena. Not only are the actual conditions as they now exist in the portion of Greenland visited minutely recorded, but general principles are discussed that have a bearing on glacial phenomena in other regions and on the interpretation of the records of formerly glaciated countries.

Among the more interesting results of these recent studies is the confirmation of the reports of previous travelers in reference to the character of the precipitous and even overhanging precipices in which the glaciers of the far north frequently end. The "Chinese Wall" described by Lockwood and Brainard, which, to persons familiar with glaciers in temperate latitudes only, appeared to be such an abnormal feature, is shown by Chamberlin to be characteristic of the manner in which Arctic glaciers terminate. Many of the photographic illustrations issued in connection with the accounts of recent studies referred to bring out this feature with almost startling reality. Two of these pictures, through the kindness of Professor Chamberlin, are reproduced on Plate 22.

Another fact of great interest is the very definite stratification of many of the glaciers in the far north. In this respect the sections displayed at the extremities of the tongues of ice extending out from the central Greenland sheet, resemble the sections exposed in the sides of crevasses in the névé regions of more southern mountains. In fact, several of the phases of the northern glaciers suggest that they correspond more nearly with the névés of Alaska and of Alpine regions generally than they do with "glaciers proper." In a certain sense they may be said to be examples of "arrested development." The glaciers of the far north, it appears, are frequently as definitely bedded and as beautifully laminated as the best examples of sedimentary rocks. This resemblance to rock exposures is still farther increased by the fact that in some instances the stratified ice

[1] "Recent Glacial Studies in Greenland," Bull. Geol. Soc. Am., vol. 6, pp. 199–220.
[2] Vols. 2, 3, and 4.

FIG. A.—FRONT OF BRYANT GLACIER, GREENLAND.

Showing vertical wall and stratification of the ice. (After T. C. Chamberlin.)

FIG. B—PORTION OF SOUTHEAST FACE OF TUKTOO GLACIER, GREENLAND.

Showing projection of the upper layers and the fluting of their under surfaces. (After T. C. Chamberlin.)

is folded and contorted in the manner frequently to be observed in gneiss and schist, and is also faulted and overthrust. These structural features may be seen in the Malaspina ice sheet and in other glaciers of temperate regions, but nowhere, so far as known, on such a grand scale or such clearness of details as in Greenland.

Accompanying and frequently intimately associated with the marked stratification of the Greenland glaciers is the occurrence of débris in well-defined layers. The scarps at the extremities of the glaciers, as stated by Chamberlin, "usually present two great divisions, an upper tract of thick, obscurely laminated layers of nearly white ice and a lower laminated tract discolored by débris. At the base there is usually a talus slope, but only sometimes a typical moraine. In the upper portion bluish solid layers separate the more porous ice into minor divisions, and these are grouped by consolidation into more massive layers. Sometimes the whole upper division consists of a single stratum, but more commonly it is divided into several great beds separated by quite distinct planes.

"The lower discolored divisions also sometimes consist of one great stratum, but oftener it is divided into many thick layers, as in the case of the white ice above. Very numerous partings further divide these beds into minor layers of varying thickness, grading down into delicate laminations, a dozen or a score to an inch."

The two strongly marked divisions exhibited by this and numerous associated glaciers seem to indicate that they were formed separately. To one studying the photographs of these glaciers the marked contrast between the upper and lower portions suggests that the upper layers of clear ice have advanced upon the lower dirt-stained layers after the débris they contain had been concentrated by melting. The two divisions would thus represent two separate stages of ice advance. As this explanation is not touched upon by Chamberlin, however, it is probable that there are insuperable objections to it, and that the true reason of the contrast referred to is less obvious and not fully understood.

After discussing the various ways in which glaciers may become stratified, Chamberlin summarized his conclusions as follows : "It would appear that the stratification originated in the inequalities of deposition, emphasized by intercurrent winds, rain, and surface melting ; that the incipient stratification may have been intensified by the ordinary processes of consolidation ; that shearing of the strata upon each other still further emphasized the stratification and developed new horizons under favorable

conditions; that basal inequalities introduced new planes of stratification, accompanied by earthy débris, and that this process extended itself so far as even to form very minute laminae."

Another phenomenon displayed in a wonderful way at the extremities of the Greenland glacier, and not previously noted in other regions, is the manner in which certain layers jut out from the faces of the ice cliffs so as to form projecting cornices. Their appearance is shown in Fig. B, Plate 22. These projections were seen on almost every one of the vertical glacial faces examined, and were found to vary in width from a few inches to one or two feet, and in rare cases to reach eight, ten, or fifteen feet. The under surfaces of the cornices are frequently fluted, as may be seen in the accompanying illustration. These cornices at first sight appear to be due to a thrusting forward of the edge of an individual layer beyond the next layer below. Movement along shearing planes seems, then, to be indicated. As shown by Chamberlin, however, if this process is really in action, the results produced by it in the unequal extension of various layers at the extremities of the glaciers, are modified and masked to some extent by unequal melting. Each layer of clear ice which projects so as to form a cornice usually has a dark dirt-stained layer below it. The dark layer absorbs heat more rapidly than the clear ice and is consequently melted back more rapidly. The fluting on the under side of the cornices, which it was supposed might be produced by the ice being pushed forward over stones or inequalities in the layer beneath, was found on further study, to be due, to a considerable extent at least, to water which trickled down the face of the overlying layer. In some instances, however, the junction plane between a projecting layer and the stratum beneath was itself found to be fluted. This and other evidence favors the idea that planes of shear are the initial cause of the unequal projection of various layers in the terminal escarpments. The development of such planes of shear seems at first opposed to the commonly accepted explanation of the character of glacial motion, but as the cornices are formed by the advance of layers of clear ice over other dark layers, the shearing planes may be due to unequal rigidity caused by the débris in the lower layer, and thus still be in harmony with the hypothesis that ice flows as a plastic solid.

Measurements made by Lieutenant Peary, of the flow of Bowdoin glacier, in about latitude 77° 45′, showed that the rate during the month of July was four-tenths of a foot at the southwest point, near the east border, and 2.78 feet at the farthest point, near the center, with an average of 1.89 feet for the whole.

One of the most interesting of Chamberlin's discoveries, as previously mentioned, is the presence of a small driftless area, on the shore of Bowdoin bay, in which the rocks are deeply decayed. Evidence is thus furnished that no great extension of ice in the region referred to has occurred within recent geological times. It is to be remembered, however, that Ingefield gulf is to the west and on the side of the great Greenland ice sheet, the flow of which is supposed to be mainly southward. The tongues of ice that come down to the sea, or approximately to that level, may be the lateral drainage of the partially stagnant border of the main snow field, and consequently would be less affected by an increase in accumulation than the secondary glaciers farther south.[1]

Since Chamberlin's visit to Greenland in connection with the second Peary relief expedition, a third expedition of the same character visited that region in the summer of 1895. Prof. R. D. Salisbury was a member of this last company, and, it is to be expected, will make many additions to the glacial observations previously obtained. Salisbury's reports will probably be published in the Bulletin of the Geological Society of America and in the Journal of Geology.

[1] I have been led to make this suggestion from certain occurrences observed in Alaska. Hayden glacier, to the east of Mount St. Elias, flows past the head of a deep, high-grade lateral valley without sending a tongue of ice into it. In ascending the lateral valley one sees in front of him a wall of ice 150 or 200 feet high, formed by the border of Hayden glacier. The ice in this wall is practically stagnant and protrudes but slightly into the lateral valley, although the central current of the glacier flows past its entrance and joins the Malaspina ice sheet several miles to the south. The conditions there seem to be similar, although on a much smaller scale, to those found in the Ingefield region. It thus appears possible that a decided increase in the main Greenland ice sheet might occur, the direction of flow being southward, without greatly changing the conditions in the lateral ice tongues that branch off from the side of the main current. These conditions may also account for the extreme sluggishness of the small glaciers about Ingefield gulf.

CHAPTER VIII.

CLIMATIC CHANGES INDICATED BY THE GLACIERS OF NORTH AMERICA.[1]

It has been shown by Dufor[2] and others that in general the glaciers of Europe and Asia are retrograding; that is, their extremities are withdrawing farther and farther up the valley through which they flow. Similar changes are known to be in progress in the glaciers of the southern hemisphere, but whether a general recession is there in progress has not been satisfactorily determined. The changes observed in the glaciers of Europe and Asia make it important to ascertain if evidence of similar climatic oscillations can be obtained from a study of the ice bodies of North America. Whether the observed variations in the lengths of existing glaciers are wholly due to changes in their climatic environment, or are influenced to some extent by other conditions, will be briefly considered in the closing paragraphs of this chapter.

In the preceding portion of this book several references have been made to recent changes in the glacier described. The bearing of these observations, however, on the study of the conditions governing the origin, growth, and decadence of glaciers, and on still wider generalizations in reference to the origin and decline of glacial epochs, is such as to warrant some repetition.

The evidence thus far gathered concerning recent changes in the glaciers of North America is remarkably consistent, and shows that with the exception of a single glacier in Alaska and perhaps also of some of the Greenland glaciers, they are all experiencing a general retreat. It must be remembered, however, that no precise and accurate studies in this connection have been made. Almost all of the information in hand is of a qualitative character, obtained for the most part incidentally in connection with other studies. While the conclusion that the glaciers are retreating is apparently well founded, more detailed observations will

[1] This chapter is a reprint, with slight modifications, of a paper by the writer in the American Geologist, vol. 9, 1892, pp. 322–336.

[2] Bull. Soc. Vaud. Sc. Nat., vol. 17, 1881, pp. 422–425.

probably show that this is accomplished by many minor oscillations which may include periods of local advance.

Character of the Evidence. — Evidence of the advance or retreat of the ends of alpine glaciers, or of the borders of piedmont and continental glaciers, may be obtained in various ways. Glaciers which are advancing sometimes plow into the débris in front of them and force it up in concentric ridges, usually with the formation of cracks in the soil. The surfaces of the ridges formed in this way are frequently covered with vegetation, which in addition to their forms and the character of the material of which they are composed, serves to distinguish them from terminal moraines. When a glacier advances into a forest, the trees are broken off and piled in confused heaps about the margin of the ice. The upper surface of a glacier is known to flow faster than the ice below, and an advance is probably accomplished by the upper surface flowing over and burying the ice which rests on the ground. For this reason advancing glaciers usually present bold scarps at their extremities, and in general, are not covered with a broad sheet of débris.

In retreating glaciers the layers of new snow deposited on the névé fields and changing to ice as they flow downward are melted before reaching the end of the ice streams, and the slow-moving ice at the bottom is thus left exposed and melts away. The retreat is accomplished not by a contraction of the ice body, but by the melting of its distal extremity. The ice which is not covered by the advance of fresh layers, melts at the surface, and the englacial débris is concentrated at the surface. When a sheet of débris of this character is extensive and covers the lower portion of a glacier from side to side, it indicates that the ice beneath is practically stationary and consequently is melting and retreating. The ends of retreating glaciers frequently have a gentle surface slope, and in many instances are so completely concealed by débris that the actual terminus of the ice cannot be distinguished. When the moraines are heavy, however, and especially when they are clothed with vegetation, the melting of the ice beneath is greatly retarded, and in some observed instances the glaciers thus protected terminate in bold scarps.

When the end of a glacier recedes more rapidly than soil can form on the abandoned area, so as to admit of the growth of plants, a desolate tract is left about its end, on which concentric lines of stones and boulders may indicate halts in the retreat. Barren areas of this nature, when the lack of vegetation is not due to the action of water from the ice, are good

evidence of recent glacial recession. When glaciers which flow through a valley having steep sides, become stagnant, a general lowering of the surface, decreasing up stream, takes place, which leaves the bordering slopes bare of vegetation. The action of rain and rills on such surfaces may indicate to some extent the length of time they have been exposed. The presence of fine glacial débris on slopes from which it would be easily washed by rain may also furnish evidence in the same connection. Retreating glaciers sometimes leave detached masses of ice which are melted in the course of a few years, and hence when present indicate rapid changes. The amount of sub-aërial erosion on glaciated areas may also serve to indicate the length of time they have been exposed.

These various classes of evidence usually enable one to determine definitely whether a glacier has recently advanced or retreated, and may sometimes afford a clue to the rate of these changes. When an opportunity is afforded for detailed study, various surveying and photographic methods may be employed. If observations can be continued season after season, the limits of a glacier at various times may be recorded by monuments, by marking the position of its margin with asphaltum, etc. Instructions in this connection have been published by Prof. H. F. Reid.[1] In the study of the glaciers of America we have, with the exception of Muir glacier, no definite quantitative measurements, and must rely on such phenomena as have been indicated.

California. — Some of the small glaciers in the High Sierra, as already described, have barren areas about their extremities, showing that they are slowly receding. No measure of the rate of this recession has been attempted.

Observations by J. S. Diller, of the United States Geological Survey, on Mt. Shasta indicate that the glaciers in northern California, like those farther south, are retreating. Evidence of this is furnished by barren areas about the ends of several of the glaciers and by a conspicuous lateral moraine on the side of the Whitney glacier, which in 1887, was about twenty-five feet above the level of the adjacent ice.

Oregon and Washington. — The glaciers on the Cascade mountains have been visited by a number of persons, but I have been unable to

[1] "The Variations of Glaciers," Journal of Geology, vol. 3, 1895, pp. 278–288. This paper contains references to other publications in which methods of observing changes in glaciers are described.

obtain satisfactory evidence of advance or recession. An inspection of photographs of the glaciers on Mount Rainier indicates that they end in areas bare of vegetation, which presumably were recently occupied by ice.

British Columbia. — The glaciers of British Columbia, although numerous and important, are but imperfectly known, and only a few observations on recent changes have been made. Many of these glaciers, however, have been seen by Dr. G. M. Dawson, who informs me that in no instance are there evidences that they have recently advanced, and that he considers it safe to assume that they are either stationary or slowly receding.

R. G. McConnel, of the Canadian Geological Survey, has kindly informed me that the glaciers, both on the Stikine river and in the Rocky mountains, have shrunken back from fresh-looking moraines, and that the intervals between the ice and the moraines, in all instances examined by him, were destitute of trees and contained but little vegetation of any kind. In his opinion a marked retreat has occurred within the last century or two, but whether it has been in progress during the past one or two decades cannot be decided from the evidence in hand. Observations made by Macoun and Ingersoll confirm this conclusion.[1]

The Illecellewaet glacier at Glacier station, on the Canadian Pacific Railroad, in the spring of 1891, was bordered by a barren area, between the ice and the encircling forest, several hundred yards in breadth, which had evidently been but recently abandoned by the glacier. A small moraine on the western side of the glacier also suggested a recent shrinking of the ice. The evidence of a recent retreat of this glacier has also been noted by W. S. Green.[2]

An absence of vegetation about the extremity of one of the glaciers on Stikine river was noted by Blake,[3] and may probably be taken as an indication of a recent retreat of the ice. A legend current among the Stikine Indians indicates that two glaciers on opposite sides of the stream were formerly united and that the river then flowed through a tunnel beneath the ice.

[1] "Mountaineering in British Columbia," by Ernest Ingersoll, Bull. Am. Geog. Soc., vol. 18, 1886, p. 18.

[2] "Among the Selkirk Glaciers," London, 1890, p. 69.

[3] American Journal of Science, vol. 44, 1867, pp. 96–101.

Alaska. — The evidence that a general retreat of the glaciers of Alaska is still in progress is abundant, and in a few instances is of quantitative value.

Lynn Canal. — About this magnificent inlet, as previously described, there are many ice streams of the alpine type, which descend nearly to sea level, but none of them are now actually tide-water glaciers. About the ends of many of them there are dense forests of spruce trees which must have been growing for at least one hundred and fifty years, but between the forests and the present terminus of the ice there is, in several instances, a barren area covered with morainal and alluvial deposits and bearing every indication of having but recently been abandoned by the glaciers.[1] These conditions are especially noticeable at the extremity of the Davidson glacier. Between the present terminus of the ice and the encircling forest there is a barren tract half a mile broad, which has been left by a retreat of the ice so recently that vegetation has not been able to take root upon it. A decided retreat of the ice has here recently occurred, and to all appearances is still in progress, but no observations of its rate have been made.

Conditions similar to those seen at Davidson glacier were observed in connection with several other ice streams in the same region. In Taku inlet, the Norris glacier comes down to sea level, but is separated from the water by broad mud flats. There is no indication that this glacier has recently advanced, and an accumulation of débris over its surface and about its extremity indicates that it is melting away. The Taku glacier, near at hand, is of the tide-water type; and evidence of recent changes in the position of its terminus is wanting.

Glacier Bay. — The evidence of recent changes in Muir glacier has been presented by Professor Wright,[2] who has shown that it has quite recently been both more extensive and of less size than at present. Additional evidence of these changes has been supplied by Reid,[3] who concludes that Muir glacier and other ice streams now discharging into Glacier bay, were formerly much more extensive than at present, and at the time of Vancouver's expedition, in 1794, probably occupied the whole of the

[1] Bull. Geol. Soc. Am., vol. 1, 1890, p. 152.

[2] "The Ice Age in North America," by G. Frederick Wright, New York, 1889, pp. 51–57.

[3] "Studies of the Muir Glacier," by H. F. Reid, in National Geographic Magazine, vol. 4, 1891, pp. 34–42.

bay to a point some distance below Willoughby island. The retreat during one hundred years is thought to be in the neighborhood of fourteen miles. This conclusion, however, rests on certain passages in the narrative of Vancouver's voyage,[1] which may possibly refer to floating ice, and not to actual glaciers, and therefore do not have the quantitative value indicated above. But under any plausible rendering of Vancouver's account it does not seem possible to escape the conclusion that the ice in Glacier bay was far more abundant at the time of his visit than in recent years.

Observations made by Wright and Reid in 1886 and 1890, respectively, show that Muir glacier has retreated during this interval more than 1000 yards. This observed rate of recession would, if continuous for one hundred years, produce a retreat of approximately fifteen miles, and affords ground for believing that the great retreat supposed to have occurred since Vancouver's visit is approximately correct.

John Muir has kindly contributed the following note concerning the retreat of the glaciers of southeastern Alaska, which confirms the evidence already presented:

"All the glaciers that have come under my observation in southeastern Alaska have retreated and shallowed since first I became acquainted with them in 1879 and 1880. Those in which the declivity of the channels is least have of course receded the most. During the ten years between 1880 and 1890, Muir glacier has receded about one mile, at its mouth in Muir inlet."

St. Elias Region. — Much space could be occupied in recording observations which indicate a general recession of the glaciers about Yakutat and Disenchantment bays and along the adjacent ocean shore, but a brief summary of this evidence is all that seems necessary at this time.

The lower portions of a large number of glaciers in this region are completely covered by continuous sheets of débris which has been concentrated at the surface through the melting of the ice. This débris is not being carried forward and deposited in terminal moraines, but is distributed over the surface of the ice in a thin sheet, and marks the stagnant condition of the glaciers on which it rests. In several instances, especially on the outer border of the Malaspina glacier, the moraines resting on the ice are clothed with vegetation, which over many square miles forms a dense forest, composed principally of spruce trees, some of which are three feet

[1] "Voyage of Discovery around the World," by Vancouver, vol. 5, pp. 420–423. Quoted by Wright in "Ice Age of North America," pp. 55–57.

in diameter. Within the forest-covered border and forming a belt concentric with it there is a barren tract covered with stones and boulders. The forests growing on the glacier and also thousands of lakelets, both in the outer border of the barren moraine and in the adjacent forest-covered moraine, indicate conclusively that the ice sheet is stagnant and consequently wasting away. On the coast bordering the Malaspina glacier on the south, there were formerly two projections called Point Rio and Cape Sitkagi, which were noted by the explorers one hundred years ago. In traversing this coast in 1891 I found that no capes exist at the localities referred to. At the site of Cape Sitkagi there is evidence that the sea has recently invaded the glacial boundary. On the sides of many of the alpine glaciers in the adjacent mountains there are steep slopes bare of vegetation although well below the upper limit of tree growth on adjacent areas, which indicate that the ice streams have recently shrunken within their beds. My conclusion after two visits to the glaciers in the St. Elias region is that without exception they are rapidly retreating.

Near Point Manby there is a locality where the Malaspina glacier has recently advanced about 1500 feet into a dense spruce forest, cutting off the trees and sweeping them into confused heaps. After advancing the ice retreated, leaving a typical morainal surface covered with lakelets. This is the only instance of a recent advance that has come under my notice in Alaska.

The head of Yakutat bay was visited by Malaspina in 1791, and again by Captain Puget in 1794. Each of these explorers found the inlet blocked by a wall of ice from shore to shore. No other observations in this connection were made until my visit in the summer of 1890.[1] From what may now be observed it is evident that the Turner and Hubbard glaciers, which come down to the water at the head of the inlet and break off in bergs, must have extended some five or six miles beyond their present position at the time of Malaspina's and Puget's visits, and were then united so as to completely block the entrance to Disenchantment bay, which is a continuation of Yakutat bay. These observations show conclusively that the glaciers mentioned have retreated five or six miles within the past one hundred years. The small recession that has here taken place, in comparison with the changes reported in Glacier bay, during the same time, is probably due to the fact that the névé from which Muir

[1] Map indicating the position of the ice in 1791 is shown on Plate 7, and its extent in 1890 on Plate 8, of my "Report on an Expedition to Mount St. Elias," in National Geographic Magazine, vol. 3.

glacier flows is much lower than the snow fields drained by the Hubbard and Turner glaciers, and presumably more sensitive to climatic changes.

North Side of the St. Elias Mountains. — Dr. C. Willard Hayes, of the United States Geological Survey, in crossing from Selkirk house on the Yukon river to Copper river in 1891, passed for a portion of the way along the northern border of the great system of mountains which culminates in Mount Logan and Mount St. Elias, and discovered several large glaciers of the alpine type flowing northward from the névé field north of Mount St. Elias, and also other glaciers draining névé fields about Mount Wrangell and flowing southward. Respecting the evidence of recent changes in these glaciers, Dr. Hayes has kindly supplied the following notes:

"Two large glaciers and many small ones were seen flowing from the St. Elias mountains northward into the White River basin. Another flows from the southeast into the pass and drains into both the White and Copper River basins. About the head of the Nizzenah are four large and many small glaciers. Flowing into Copper river from the coast range are four or five glaciers, one of them — Miles glacier — being larger than any seen further in the interior. Observations were thus made on twelve glaciers, and, with one exception to be described later, all show a more or less rapid recession. The evidence of this recession in most cases is the accumulated moraine covering the terminal edge of the glacier; or where there is not sufficient englacial drift to accumulate and form a protective mantle, the stagnant ice melting to a feather edge. The White River lobe of Russell glacier is of the moraine-covered type, while the Nizzenah lobe has the feather edge. On the Klutlan and Russell glaciers the outer portion of the moraine-covered ice supports a dense vegetation, which becomes gradually more scanty and disappears about half a mile from the edge of the ice. The recession of the smaller glaciers along the Nizzenah appears to have been more rapid than the advance of the vegetation, so that between it and the ice there is a belt of bare moraine.

"Miles glacier terminates in an ice cliff fronting upon Copper river, and the river has as yet cut only part way through the dam formed by the northern lateral moraine. This moraine must, until very recently, have been backed up by the glacier itself, though the front of the latter has now retreated two miles to the eastward.

"While the fact of recession is manifest, the rate is more difficult to determine. In one case, however, it is possible to connect the amount of recession with an important episode in the history of the region, namely,

the eruption of a widespread deposit of volcanic ash which extends from near the head of the Pelly westward to Scolai pass. With regard to the age of this deposit Dr. Dawson says:[1] 'While the eruption must have happened at least several hundred years ago, it can scarcely be supposed to have taken place more than a thousand years before the present time.'

"For a distance of about three miles in front of the Klutlan glacier there is a deposit of moraine material perhaps 200 feet thick, composed of volcanic ash and angular rock fragments. This evidently fixes the position of the glacial front at the time of the volcanic eruption, and the amount of recession since that event. It is interesting to note that on the present glacier surface the volcanic ash is found only a short distance from the end, showing that since the eruption, while the front of the glacier has receded about three miles, nearly the whole mass of the glacier has been renewed by fresh addition from its source.

"The single exceptional case already referred to is the Frederika glacier, which seems to be advancing its front instead of retreating. It has its source in the high mountains forming the eastern members of the Wrangell group, and flows south in a lateral valley, joining the valley of the Nizzenah at right angles. The front of the glacier is parallel with the river and about three-fourths of a mile from it, the intervening space being a gravel plain. The glacier terminates in nearly a vertical ice cliff about 250 feet high. It is slightly convex, and stretches entirely across the valley, about a mile in length. The surface of the glacier is free from moraines, but is extremely rough and broken, unlike the ordinary surface of stagnant ice at the end of a retreating glacier. At the foot of the cliff is a small accumulation of gravel and fragments of ice, probably pushed along by the advancing mass.[2]

"An explanation of this anomalous case is suggested. Ten miles to the westward of the Frederika another much larger glacier flows into the valley of the Nizzenah. This is formed by the union of three separate streams, and of these the eastern appears to be retreating much more rapidly than either of the others. But this eastern branch probably has its source in the same basin as the Frederika glacier, and it seems not impossible that by some means the drainage has been diverted from the western to the eastern outlet, thus causing the rapid retreat in the former glacier and advance in the latter."

[1] Report on Yukon District, p. 45, B.

[2] This is the only authentic instance of an advancing glacier known on the west coast of North America. I. C. R.

Greenland. — Regarding recent changes in the ice sheet of Greenland there is but scanty evidence, and such observations as have been made on the advance and retreat of the margin of the ice are conflicting. Holts found in 1880, between latitude 61° and 65° 30′, on the west coast, according to Lindahl,[1] that "the border of the ice appeared to have retreated quite recently in many places; in others, it had decidedly advanced." Nansen[2] remarks in this connection that we cannot even conjecture what the present conditions are, and thinks that the observations show that there is no strong tendency either toward advance or retreat. Warren Upham,[3] who has recently reviewed the literature relating to the Greenland ice sheet, informs me that in his judgment the ice is now slightly increasing in thickness and generally in extent. This conclusion rests largely on the general absence of débris on the borders of the ice sheet. His studies have also led him to the conclusion that Greenland, in common with other portions of the northeast border of this continent, is now having an appreciable increase in cold.

The observations of those who have traversed the inland ice agree in showing that nearly its entire surface is in the condition of a névé, and suggest that growth and not retreat must be in progress. The absence of débris on the borders of the ice sheet referred to by Upham, is important in this connection, and seems to indicate that no great waste of ice occurs before it is discharged into the sea. So far as one may judge from the observations of others, it seems as if the evidence available points to an increase of the ice sheet, as supposed by Upham; but the accuracy of this conclusion is questionable, and Dufor, in a paper cited in the beginning of this chapter, is inclined to the opposite opinion. He states that in 1880, he made a communication on the retreat of the glaciers of Europe and Asia before a scientific congress at Reims, and that, during the discussion which followed, one of the persons present who had been in Greenland several times mentioned that he "had noticed that the glaciers of that land had also retreated considerably." It is known that the glaciers of Greenland were much more extensive during a former epoch than at present, and left records at an elevation of 3000 feet above the present ice surface.[4]

[1] American Naturalist, vol. 22, 1888, p. 593.

[2] "First Crossing of Greenland," vol. 2, p. 491.

[3] The conclusions of Mr. Upham are also contained in the following papers: "On the Cause of the Cold of the Glacial Epoch," American Geologist, vol. 6, 1890, p. 336; and "The Ice Sheet of Greenland," American Geologist, vol. 8, 1891, p. 150; "Criteria of Englacial and Subglacial Drift," American Geologist, vol. 8, 1891, p. 385.

[4] American Journal of Science, Third Series, vol. 24, pp. 100, 101.

It may be suggested that the observations referred to by Dufor possibly relate to these ancient records.

Weight of the Evidence. — The observations summarized in this chapter in reference to the Cordilleran region, although unsatisfactory in many ways, indicate, with a single exception which seems to have a special explanation, that the ice bodies in that region are retreating. This conclusion not only rests on direct observations of several individuals, but is sustained by negative evidence as well. An advance of a glacier, especially in a forested country, is apt to be strongly marked, and would attract the attention of even a casual observer; but in no instance, with the exception reported by Dr. Hayes, and the slight extension on the border of the Malaspina glacier already mentioned, has a recent advance been reported.

The fact that the glaciers at the head of Yakutat bay have retreated several miles within the past one hundred years, as well as the still greater recession of the glaciers of Glacier bay during the same period, indicates that the present general recession of the glaciers of the Pacific coast has probably been in progress for more than a century. During this time there must have been many minor oscillations which our imperfect observations do not detect, but the conclusion that the general movement has been backward is well sustained.

Theoretical Considerations.

The variations that glaciers are undergoing have received special attention during the past few years. A large body of evidence in this connection is being collected, especially by members of various Alpine clubs, but as yet these studies have been confined principally to the glaciers of Europe. The importance of this inquiry led the International Congress of Geologists, at its meeting at Zurich in 1894, to appoint a committee for the special purpose of collecting data all over the world, with the view, if possible, of discovering a relation between the variations of glaciers and meteorological phenomena.[1] An attempt to discuss systematically the observations thus far recorded in this connection would be out of place at the present time, since no detailed studies have been made of American glaciers; but a few suggestions in reference to the directions in which this investigation seems to point may be of interest to the reader.

All the explanations of the observed variations in the length of glaciers thus far offered are based on the supposition that they are due to

[1] H. F. Reid, "Variations of Glaciers," Journal of Geology, vol. 3, 1895, pp. 278–288.

climatic changes. In respect to the greater oscillations it seems as if no other conclusion could be expected, but minor changes, as I shall attempt to show, may be due to other conditions.

The statement made in the opening paragraph of the present chapter, to the effect that the glaciers of Europe and Asia are retreating, is perhaps misleading, as it refers to the algebraic sum of advances and retreats during a term of years. Within the cycle referred to there have undoubtedly been many minor fluctuations which vary not only in amount but in direction, in different glaciers. In several instances, certain members of a group of glaciers have advanced during recent years, while others in the same group have remained stationary or retreated, and *vice versa*. Opposite movements in glaciers which so far as one can judge are exposed to the same climatic changes have not been satisfactorily explained.

Changes in the length of a glacier may evidently result from (1) variations in the amount of snow supplied to its névé region, (2) to changes in the rate of melting, or (3) to fluctuations in the rate of flow.

Variations in the amount of snow added to the névé of a glacier, as shown in part at least by Professor Forel,[1] may be considered as of the nature of a pulsation which is propagated throughout its length. The end of a glacier might therefore alternately advance and retreat in sympathy with variations in snowfall that occurred scores of years and even centuries before. Two glaciers subject to the same climatic conditions, but of unequal length, or of the same length but having different mean velocities, would advance or retreat at different periods for the reason that the time required for the increment produced by an increase of snowfall to reach their extremities would be different.[2]

It has been suggested that variations in the rate of melting might be a factor causing the ends of glaciers to advance or retreat. But as loss by melting is greatest at the lower extremity of a glacier, similar effects would be expected in neighboring instances, although alpine glaciers that

[1] Bibliot. Univ. de Genève, 1881.

[2] Another explanation dependent on variations in snowfall has been suggested by Professor Richter, who, as stated by Reid (Journal of Geology, vol. 3, p. 281), "thinks that the accumulation of snow in the névé region, even under uniform meteorological conditions, would in time produce a great enough pressure to overcome the resistance, due to the friction against its bed, of the glacier's tongue, which is then pushed forward with a greater velocity, resulting in the advance of the glacier; this continues until the drain on the névé region, on account of more rapid flow, exhausts the accumulation of snow; after this the motion almost entirely ceases, and the glacier melts back until another advance begins. Professor Forel calls this the 'theory of intermittent flow,' and points out that according to it variations in the size of glaciers would be entirely independent of meteorological changes."

descend into different valleys might perhaps be influenced differently. It is unnecessary to discuss this suggestion, however, since observation on meteorological changes and on the variations of glaciers in the same region do not sustain it.

While it is customary to refer the advances and retreats observed in glaciers to climatic changes, and although opposite movements in glaciers exposed to the same meteorological conditions may, perhaps, as shown above, be explained in this way; yet I venture to suggest that there is a principle involved in the behavior of glaciers themselves that might bring about analogous results. I refer to the influence of débris on the flow of ice containing it.

As is well known, a concentration of débris takes place at the end of a glacier, especially when it is slowly retreating. This is due to the fact that while the volume of the ice decreases, the amount of débris it contains remains practically the same. The percentage of foreign material in a given volume of ice is thus increased. The rate of flow of ice, however, other conditions remaining the same, decreases as the percentage of contained débris increases.[1]

As the percentage of débris in the extremity of a glacier increases, the flow of the ice will slacken, and when the concentration reaches a certain point, stagnation will result. The débris-charged ice will then act as a dam and check the flow of the clearer ice above. The effect of such a check in the advances of the stream will vary with conditions, particularly as there is a delicate adjustment at the extremity of a normal glacier between the effects of temperature tending to melt the ice and the advance of fresh ice from above. Fresh ice may advance upon the débris-charged portion and become in turn concentrated, thus raising the dam; or, in the case of a growing glacier, may flow over the obstruction and continue to advance until melting and concentration of débris again causes stagnation at its extremity, when the process would be repeated. If the glacier is slowly wasting away, the dam would check the advance of ice from above and cause it to increase in thickness and to expand in area, thus presenting a broader surface to the atmosphere. Now, the presence of surface débris influences the melting of a glacier in two ways. When small in amount, especially if dark in color, it promotes liquefaction; but if abundant, it protects the ice from the sun and atmosphere and retards waste. In the case of a slowly retreating glacier that has formed a débris-charged ice

[1] I. C. Russell, "The Effect of Débris on the Flow of Glaciers," Journal of Geology, vol. 3, 1895, pp. 823–832.

dam, the melting of the clear, or but slightly charged ice, above the obstruction will go on much more rapidly than at the extremity, where the ice is covered with earth and stones. The ice above the obstruction might then be melted, leaving the dam to slowly waste away and finally leave a terminal moraine. The retreating glacier by again concentrating débris in its extremity would again halt, and the process be repeated.

An explanation is thus suggested of the varying behavior of glaciers under the same climatic conditions. Two glaciers supplied in their névé regions with equal quantities of snow, and alike in all respects except in the amount of débris carried, would undergo the changes outlined above at different rates. If their percentages of débris were the same and other conditions varied, their periods of halt and advance or retreat would again vary. So diverse are the conditions controlling the flow of glaciers that in no two instances would their pulsations be synchronous, even under the same meteorological environment.

While the greater changes exhibited by glaciers can only be accounted for by variation in the supply of snow on their névés, or changes in the rate of melting, or both of these causes combined, due to meteorological fluctuations, it seems evident that the minor advances and retreats of their extremities may be due in part to the effects of débris on the flow and on the melting of the ice as outlined above.

CHAPTER IX.

HOW AND WHY GLACIERS MOVE.

A REVIEW of the various hypotheses that have been advanced to account for the movements characteristic of glaciers, necessitates an extension of the geographical limits set for this book, since the critical investigation of glacial phenomena was well advanced in Europe before the fact that glaciers existed in North America, with the exception of the remote Greenland region, was known. It is only in recent years that the detailed study of existing glaciers has been undertaken in this country. Although Agassiz adopted America as his home, the investigations that placed him in the foremost rank of glacialists were carried out in Europe. It is to the physicists and geologists of Europe that we are indebted for nearly all that has been done respecting the philosophy of glacial motion.

The Nature of Glacial Flow. — Many observations have been made which show that glaciers have motion, and in probably all instances exhibit a well-defined flow during some portion of their history. Although this matter has claimed a large amount of attention, it is important to remember that glacial ice frequently does not flow, and that probably some part of every glacier is stagnant.

The fact that glaciers move was first determined in a qualitative way by noting the changes that take place in the moraines on their surfaces. Conspicuous boulders resting on the ice were observed to slowly change their positions from year to year with reference to fixed points on adjacent cliffs. These crude observations lead to measurements of the rate of flow. In the case of several glaciers of the alpine type, rows of stakes have been placed in the ice at right angles to the direction of movement, and their displacement observed by means of surveying instruments from the adjacent banks. In this manner changes in the positions of the stakes have been measured from day to day, and in some instances even from hour to hour. Many observations of this nature have shown that in the case of a river-like glacier, the most convenient variety for study, the maximum motion is in the central part and decreases toward the borders. It has also been found that the rate of flow is greatest at the surface, and decreases toward the bottom. When a glacier follows a sinuous course, the thread

of maximum current is deflected to the right and left of a medial line, in the same manner that the swift central current of a winding river is thrown first against one bank and then against the other; but the bends in the sluggish ice current are less abrupt than in the case of the more flexible water current.

The rate of flow of a glacier varies from locality to locality, throughout its length, in response to irregularities in the valley it occupies, unequal distribution of the débris it carries, and other reasons. The rate of flow also varies with the seasons, being greatest in summer and least in winter. Similar but much less pronounced variations occur between day and night. These seasonal and daily changes coincide with variations of temperature, the rate of flow increasing with an increase in the amount of heat that reaches a glacier. It is important to note, however, that although glaciers are sluggish in cold weather, they continue to flow, in many instances at least, even in the depth of winter. A flowing motion in the ice of piedmont and continental glaciers is frequently evident from the arrangement of débris on their surfaces. The same fact is shown, also, by the presence of lobes about their margins which many times become well-defined streams. Although no measurements have been made of the manner in which the currents in great ice sheets move, there is no reason for supposing that the causes producing them are of a different nature from those which urge an alpine glacier through a narrow valley. If an explanation can be found for the flow of a mountain ice-stream, it is evident that it should explain the movements of other types of glaciers as well.

The movements of a glacier are usually greatly modified by local conditions. In seeking for general laws applicable to all glaciers, it will be of assistance if we can determine what would be the behavior under normal conditions of an ideal glacier composed of clear ice, flowing down a straight, even channel of uniform width and with a uniform gradient both of the valley and of the glacier's surface. Let us assume also that in cross section our ideal glacier has the form of half an ellipse, the division being along the longer axis. From what is known concerning the behavior of glaciers we may determine in what manner our ideal ice stream would flow.

All students of glacial phenomena will agree, I think, that in the ideal example before us the thread of maximum current would be at the center of the surface, and that the rate of surface flow would decrease uniformly toward each bank; also, that the rate of flow would decrease uniformly from the center of the half-ellipse along any of its radii. The minor axis of the ellipse would divide a cross section of the glacier into two equal and

similar figures, and similar points in each half would have a corresponding motion which would differ from the motion of all other points in the cross section.

Any theory of glacial motion that is applicable to all glaciers should account for the flow of our ideal glacier, and also explain all changes in its movements resulting from alterations in the assumed conditions. With a true and sufficient explanation of glacial motion in mind, we should be able to predict what modifications in the flow of our ideal glacier would result: if, for example, its channel was no longer straight; if changes should be made in the gradient of either its bottom or surface; if the sides or bottom of its channel should be made uneven; if its width should vary; if the temperature to which it is exposed should change either gradually from its source to its extremity, or fluctuate irregularly; if the ice should become unevenly charged with débris; and in fact any other changes in environment to which actual glaciers are subject.

The student who has in mind the movements in our ideal glacier, and attempts to trace the changes that would result from such a combination of conditions as exert an influence on even the simplest existing alpine glacier, will no doubt be willing to accept the conclusion reached by glacialists that in any existing glacier, no two points in any cross section, and in fact no two points in any portion of the ice stream, move at the same rate for any considerable time. In other words, adjacent molecules — or other small divisions into which ice may be assumed to be divided — throughout a glacier are moving at different rates.[1] That is, the flow of glacial ice, in a general way, at least, is analogous to the flow of a liquid,

[1] Observations by Messrs. R. H. Koch and Fr. Klocke (Philosophical Magazine, Fifth Series, vol. 9, 1880, pp. 274–277) on the movements of a point in a vertical plane in a glacier indicate that the movements of such a point are much more complex than has been generally supposed. In the observations referred to it was found that a given point at one time moved toward the source of the glacier, and at another time toward its extremity. Two adjacent points were found to move in opposite directions at the same time. The maximum movements occurred in the forenoon, beginning with the irridation of the glacier by the sun. These morning movements were irregular, but on the whole tended down the valley; while at night the resultant in the direction of movement was toward the mountains.

So far as I am aware, these delicate observations have not been repeated, and conclusions based on them may not apply to glaciers in general.

Messrs. Koch and Klocke do not state what precautions were taken to shield their instrument from changes of temperature, and it is possible that their observations are in error from this cause. The difficulty of keeping a transit or other similar instrument in adjustment, when exposed to changes of temperature, makes it desirable that the observations referred to should be repeated with an instrument so arranged, perhaps with a prism, that a fixed point on land can be seen at the same time that the movements of a point on a glacier are measured.

or more nearly to the flow of a viscous fluid. It must be remembered that in the above attempts to describe the flow of an ideal glacier, and to suggest the nature of the changes that would result from modifications in the conditions to which it is subjected, the aim has been to obtain a graphic idea of *how* a glacier flows, without attempting to explain *why* it flows. In order to learn if possible the nature and mode of action of the natural forces which cause ice to move, and at the same time become more familiar with glacial phenomena in general, let us review briefly some of the principal explanations that have been offered of glacial motion.

Hypotheses of Glacial Motion.[1]

Several hypotheses in explanation of the characteristic movements of glaciers have been advanced, but no one of them has thus far met with general acceptance. It is manifestly the duty of the geologist and geographer, however, to examine these proposed explanations, and ascertain so far as is possible how much of each can be safely accepted, even if it does not afford a sufficient reason for all of the movements known to occur in large ice masses. By so doing we may, perhaps, clear the way for renewed study, or possibly be able to frame an *eclectic* theory from portions of previous explanations which will be satisfactory.

The Sliding Hypothesis. — As far back as 1760, as stated by Tyndall, Altman and Grüner proposed the view that glaciers move by sliding over their beds. Nearly forty years subsequently this notion was revived by De Saussure, and has therefore frequently been called "De Saussure's theory," but is more frequently, perhaps, designated as the "sliding theory" of glacial motion. Subsequently the hypothesis was ably discussed by W. Hopkins.[2]

Under this hypothesis glaciers are supposed to slide bodily down the valleys they occupy, in obedience to gravity, and grind away the rocks over which they pass, by means of sand and stones frozen into their under surfaces.

[1] Many reviews of glacial hypotheses have been published; among those that the student will find most interesting and instructive are: "The Physical Cause of the Motion of Glaciers," in "Climate and Time," by James Croll, first edition, chapters 30, 31; "The Great Ice Age," by James Geikie, second edition, chapters 3, 4; "Illustrations of the Earth's Surface — Glaciers," by N. S. Shaler and W. M. Davis, chapter 12. The last-named book also contains a useful list of works on glaciers, published previous to 1881.

[2] "On the Motions of Glaciers," Philosophical Magazine, vol. 24, 1895, pp. 607–609: Also, "On the Theory of the Motion of Glaciers," ibid., vol. 25, 1863, p. 224.

It is unnecessary to discuss the sliding hypothesis, since, as is now unanimously conceded, the normal movements to be observed in glacial ice are of the nature of an onward flow, accomplished by the mutual displacement of molecules of ice. It is of interest to note, however, that this early and now totally rejected hypothesis does contain an element of truth.

When glaciers descend steep slopes they become broken, and even large masses sometimes move short distances by sliding bodily downward. This, it will be understood, is an exception to the normal movements characteristic of glaciers, and is referred to simply to show that even the crudest of the hypotheses we are considering contains a grain of truth.

The Hypothesis of Dilatation. — As the movements of glaciers became better known, the sliding hypothesis just referred to was supplanted by the "hypothesis of dilatation," advocated especially by Charpentier and Agassiz. The basis of this proposed explanation is that water on freezing expands and, if confined, will exert a pressure on the walls retaining it. As water penetrates freely into a glacier through fissures and capillary passages, it was concluded that it would freeze in such situations, and thus exert a pressure on the ice containing it, and that a movement of the ice would thus originate which would take the direction of least resistance ; and, as alpine glaciers were alone considered, it was concluded that the direction of least resistance would be down the valleys they occupy.

This hypothesis, like the one it displaced, met with opposition and lead to much discussion. Better still, it awakened fresh interest in glacial studies and led to renewed observations of glacial phenomena.

Among the able opponents of the dilatation hypothesis was W. Hopkins, who showed, by means of mathematical demonstrations, that the direction of least resistance to expansion at most points within a glacier would be vertically upward, and that the assumed cause of glacial flow, if really in action, would cause a glacier to increase in thickness rather than advance down a valley.

Many other objections to the hypothesis under review have been advanced from time to time. It has been shown, for example, that the changes of temperature to which glaciers are ordinarily subjected do not penetrate far beneath the surface ; and besides, if glacial flow is due solely to the freezing of water within the ice, it should be greater by night than by day, and greater in winter than in summer, which, as

we know, is the reverse of the truth. These and other objections to the hypothesis of dilatation have led to the conclusion that it is inadequate as a complete explanation of the normal movements of even alpine glaciers.

In closing this brief review of a long and instructive discussion, I wish to remind the reader that, although the hypothesis of dilatation as a whole has been abandoned, the labors of its advocates were not in vain. It not only served a useful purpose in stimulating inquiry, but that it is based on a true principle must be conceded even at this time when several younger and more promising hypotheses are in the field. It cannot be truthfully denied that water does freeze in cavities and capillary passages in glaciers, and in so doing does exert a force which tends to move them. What the opponents of the hypothesis have demonstrated is that the force appealed to is inadequate to bring about the results observed, and that it is not the only force that tends to produce glacial motion.

The Hypothesis of Plasticity. — The attempt to explain the flow of glaciers, to which this name has been applied, is based essentially on two principles: 1. That ice is plastic, and will change its form under pressure. 2. That ice in sufficiently large masses, when unconfined, will flow under the influence of its own might. Each of these propositions has been vigorously assailed, and even at the present day their correctness is not admitted by eminent physicists. More will be said in this connection in advance.

It is stated by Tyndall[1] that the first suggestion in reference to glacial ice behaving as a plastic body was made by Bordier, in 1773. This germ, however, did not bear fruit.

In 1841 Rendu presented a "Théorie des Glaciers de la Savoie" before the Royal Academy of Savoy, in which the idea that glacial ice behaves as a plastic solid is clearly enunciated. This important discussion not only of the movements of glaciers, but of many other phenomena connected with them, has been republished, together with a translation in English, and may be found in most scientific libraries.[2]

The hypothesis that glaciers owe their movements to the inherent plasticity of the ice composing them found its chief advocate in J. D. Forbes, who first applied the term *viscous* to glacial ice, and by long continued study and careful experiments sought to establish a "viscous

[1] "Forms of Water," 1875, p. 153.

[2] "Theory of the Glaciers of Savoy," Macmillan & Co., 1874.

theory" of glacial motion. The formal hypothesis, as stated by Forbes,[1] is: "A glacier is an imperfect fluid or viscous body, which is urged down a slope of certain inclination by the mutual pressure of its parts." As the terms viscosity and plasticity are now strictly defined, although applied to phenomena which in reality merge together, it is advisable to change the wording of the hypothesis under review, as first stated, without, however, altering the meaning that was intended to be conveyed. We shall speak of solids that yield continuous under pressure as a plastic solid, and a fluid which flows sluggishly as a viscous fluid.

The conclusion that an alpine glacier flows more rapidly in its central part than at the sides was first definitely established by Agassiz, and afterward verified by Forbes. The flow of a glacier was thus shown to be strikingly analogous to the flow of a river. This fact has been so well established, and may be so easily verified, that we are justified in saying that a glacier flows in the same manner as a fluid body, that is, it advances owing to differential molecular motion in essentially all its parts. Whether the flow of glacial ice is due to its plasticity under the influence of its own weight, or is owing either wholly or in part to other causes, I trust will appear as we advance.

The propositions on which the hypothesis of plasticity are based must necessarily be verified before they can be applied in explanation of the behavior of glaciers. Let us see first of all whether conclusions have been reached in reference to the plasticity of ice.

Ice, as we ordinarily see it, is a hard, brittle substance, which may be shattered into angular fragments by a sharp blow. At the first glance it would seem that scarcely any statement could be farther from the truth than to say that such a substance is plastic, that is, will yield continuously to pressure without fracture. Many substances, however, like pitch, asphaltum, etc., which at ordinary atmospheric temperatures are as brittle as ice, and like it may be broken into angular fragments by a force suddenly applied, will, if time be allowed, slowly change their form, or flow, under the influence of their own weight. Many experiments have been made which demonstrate that ice under sufficient pressure, if slowly applied, will also change its shape without being broken. Without digressing too far from the main subject in hand, I may state that perhaps the

[1] "Travels through the Alps of Savoy and Other Parts of the Pennine Chain, with Observations on the Phenomena of Glaciers," Edinburgh, 1845, second edition, p. 365. "Norway and its Glaciers," Edinburgh, 1853. "Occasional Papers on the Theory of Glaciers," Edinburgh, 1859.

most conclusive experiments in this direction have been made by J. C. McConnel and D. A. Kidd,[1] who demonstrated that a bar of glacier or other ice, if composed of many crystals, will yield continuously and without fracture to both *pressure* and *tension*. That is, it apparently behaved as a plastic solid. The greatest freedom of motion occurred when the ice experimented on was near the melting point, and decreased with a decrease of temperature. At —2° C. its "plasticity" was twice as great as at —10° C.

Further experiments, by McConnel, with bars of ice cut from single crystals, brought out most interesting results. It was found that when such a bar with the optic axis of the crystal perpendicular to two of the side faces was subject to bending stress, it would bend freely in the plane of the axis either at or below the freezing point, but not at all in a plane perpendicular to it. In the bent crystal the optic axis in any part was normal to the bent faces in that part. The crystal behaved as if it was composed of an infinite number of thin sheets of paper, normal to the optic axis, attached to each other by some viscous substance which allowed one to slide over the next with great difficulty.

The results of the experiments just cited seem to show that while ice composed of many crystals yields to both pressure and tension in a manner that is strikingly similar to the behavior of plastic substances under similar conditions, yet the manner in which it yields is decidedly different. The flow of liquids and of viscous substances is accounted for by the movement of adjacent molecules past each other, in any direction ; in ice, motion in response to pressure or tension takes place along gliding planes which have a definite relation to the optical axis of the crystals.

The movements observed in ice under pressure is not, therefore, true plasticity, but, as pointed out by McConnel, is identical in nature with the displacements along planes observed in rock salt, Iceland spar, and other certain substances when subjected to pressure. For this peculiar "plasticity" no definite name has been proposed.[2]

[1] "On the Plasticity of Glaciers and Other Ice," Proc. Roy. Soc., London, vol. 44, 1888, pp. 331-367. Also, J. C. McConnel, "On the Plasticity of an Ice Crystal," Ibid., vol. 48, 1890, pp. 256–260 ; vol. 49, 1891, pp. 323–343.

[2] The experiments by McConnel and Kidd cited above have recently been repeated by Dr. O. Mügge, and are described by Chamberlin, in the Journal of Geology, vol. 3, 1895, pp. 965, 966, as follows :

" Prisms were cut from carefully formed ice in various directions to the principal crystallographic axis, *i.e.* the optic axis of the crystal, particularly in directions parallel and transverse to it. These were tested by placing their ends on supports, and weighting them in the center. In testing the transverse prisms, the optic axis was first placed in a vertical posi-

Experiments by Tyndall on the moulding of ice into various shapes, by pressure applied with comparative rapidity, will be referred to in advance in connection with the consideration of another property of ice, namely, *regelation.*

The manner in which glacial ice moulds itself to the inequalities of the rocks over which it flows, so as, in many instances, to polish and striate the bottoms and sides of narrow trenches, and even the under surfaces of projecting ledges, is undeniable evidence that it behaves as a plastic body. One of the objections urged against the idea that ice is plastic is that although it yields to pressure, it is supposed not to yield to tension, and hence lacks one of the properties of a plastic substance. The formation of cracks in glaciers is frequently cited as proof that ice breaks under tension. This conclusion was held by Tyndall, who apparently demonstrated by delicate experiments that ice would not yield to tension except by fracture. More recent experiments by McConnel and Kidd, already cited, have shown, however, that ice does stretch under tension when slowly applied. The widening of crevasses, frequently to be observed both in névé

tion. The prisms sagged, and their ends were drawn inward. Optical examination showed that the optic axis remained normal to the bent surface. Subsequent observations on surfaces fractured for the purpose showed striation and other indications that plates of the crystal parallel to the basal plane had sheared upon one another.

"When similar prisms were placed so that these gliding planes stood on edge, no appreciable results followed, even though greater weights and longer times were employed.

"When prisms cut parallel to the principal axis were tested, the gliding planes being transverse to the prism, the weight sunk sharply into the upper face of the prism and a corresponding protrusion appeared below. As the process continued, the protrusion below kept closely parallel to the indentation above, both widening somewhat until a section of the prism had been pushed entirely out. Optical examination showed that the optic axis remained parallel to itself throughout. The block remained transparent and free from fracture. The weight appeared to have simply slipped the plates over their neighbors, carrying the adjacent ones forward with them to some extent by dragging, but not visibly affecting the more remote ones.

"If the prism be made of square cards and placed on its side, and a transverse force applied, the result will illustrate the apparent method of movement within the ice crystal in this last case. If such a prism be pressed at right angles to the cards, it will illustrate the bending of the first case, and if the cards be placed on edge, they will illustrate the effectual resistance to deformation of the first case. Variations of temperature through 10° were not found to produce notable differences of result.

"Not to mention other significant points, the investigation seems to warrant the important conclusion that ice crystals yield to deforming forces by the sliding or shearing of the crystalline layers at right angles to the principal axis. No analogy to the motion of a viscous fluid appeared. Dr. Mügge had previously found a similar method of deformation in other minerals, including gypsum, stilbite, and vivianite. In respect to its mode of internal motion, ice is therefore to be classed with these minerals, rather than bodies properly called viscous."

regions and in the ice of the lower portions of glaciers, also sustains the same conclusion. As in the case of the compression of ice, its ability to stretch under tension is lowered by a decrease of temperature.

Without attempting to review at this time all that has been written concerning the plasticity of ice, it seems safe to conclude, on the strength of the experiments and observations just cited, as well as many others which might be given, that ice under pressure slowly applied can be made to flow. That ice is truly *plastic*, however, is not sustained by the experiments. The question *how much* pressure would be required to produce the flow observed in glaciers still remains. This is a more difficult question, and perhaps does not admit of precise determination.

The conclusion reached by Forbes and others, that glaciers flow by reason of their own weight, that is, ice is sufficiently plastic to shear under the influence of gravity, has, in the opinion of many physicists, been demonstrated by the bending of planks of ice when supported at their extremities. That planks of ice will bend under such conditions has been shown by experiments, and also by observing the behavior of blocks of ice in Arctic regions, which slowly sag when supported at opposite edges, even when the temperature is continuously far below freezing. In the bending of a plank of ice under its own weight, there must of necessity be a compression of the material on the upper side and an extension on the lower side. In other words, the behavior of ice under the influence of gravity is similar to that of plastic bodies under like conditions. [1]

Certain experiments cited by Henry Moseley, however, have been claimed to show that the weight of an ice mass is insufficient to cause it to change its shape, or shear, in the manner in which many plastic solids are known to do under the influence of their own weight. But in the experiments referred to the difference in the behavior of ice under pressure when slowly applied and when applied with comparative rapidity is, in the opinion of several competent judges, not sufficiently recognized. As shown by Moseley, the force necessary to shear a column of ice one square inch in area of cross section, when applied in the course of 15 or 20 minutes, is about 75 pounds, or 34 times the computed portion of gravity available in producing glacial flow, and, therefore, these glaciers cannot move by reason of their own weight.

Moseley's experiments have been repeated by other physicists, and also, in part, by the present writer, with essentially the same results, so far as

[1] This conclusion is held by William Mathews and others. Philosophical Magazine, vol. 212, 1871, pp. 332–334.

the amount of force required to shear ice under the conditions observed in the experiments are concerned. That the conclusions reached from these experiments can be applied in explaining glacier motion cannot be so readily accepted.

The experiments made by Moseley have been discussed by J. Ball[1] and others, who have shown that the time element is important, and that there are reasons for doubting if the results reached can be applied in explanation of the flow of glaciers.

Although the conclusion that ice will flow under the influence of its own weight may not be established to the satisfaction of all who are interested in the problem, yet if applied provisionally to glaciers it is found to explain many of their movements, and enables one to predict what will occur under given conditions.

By comparing the movements of glaciers with the movements of pitch and other similar bodies under the influence of gravity, striking analogies may be obtained. If pitch of the proper consistency be placed in a gently inclined trough, having so far as practicable the proportions of a representative glacier-filled valley, it will slowly descend in the same manner that glaciers move, even though it is extremely brittle at the temperature at which the experiment is conducted. The flow of the pitch is most rapid in the central part of the surface of the stream, but decreases gradually in rate of flow towards the sides and bottom. If two streams of pitch be made to unite so as to form a trunk stream, representing a compound glacier, lines of débris on the borders of the tributaries, representing lateral moraines, will unite and form a "medial moraine." Where inequalities in the bottom of the trough exist, crevasses will appear in the pitch, etc. In this and other ways the flow of a glacier may be shown to correspond in a most striking manner with the flow of a plastic substance which is urged forward solely by the influence of its own weight. Strong as are the arguments tending to show that glaciers are urged forward in the same manner that truly plastic substances flow under the influence of gravity, this explanation has not been unanimously accepted.

Many forcible objections to the hypothesis of plasticity have recently been advanced by T. C. Chamberlin.[2] These objections, however, are based principally on observations made on the glaciers of Greenland, where the generally low temperature may be considered as reducing the plasticity

[1] "On the Cause of the Motion of Glaciers," Philosophical Magazine, vol. 42, 1871, pp. 81–87.

[2] "Recent Glacial Studies in Greenland," Bull. Geol. Soc. Am., vol. 6, 1894, pp. 199–220.

of ice to its lowest limit as exhibited in glaciers. Whether this condition, however, may render the observations less valuable for determining the existence of plasticity, or make the test more searching, might be differently concluded.

Chamberlin states that his observations seem to be adverse to anything which can be termed viscous fluency. In some instances the surfaces of glaciers were found to rise in the direction of the motion of the ice, so that surface streams flowed backward. Similar changes in surface slope were observed by the present writer in several instances in the névés of Alaska, and is evidently not exceptional. This phenomenon may, however, not be opposed to the hypothesis of plasticity, since the energy which urges forward a given molecule within a glacier is the resultant pressure of molecules at higher levels. It is principally the surface gradient that determines the rate of flow. The formation of elevations analogous to anticlinal folds may be due to the pressure of ice at higher elevations, acting as a thrust on the edges of layers, the cohesion of which is sufficient to allow them to bend upward and reverse the normal surface gradient.

The breaking of glacial ice under moderate and slowly acting tension was also observed by Chamberlin, who concludes, as others have done, that if the ice could stretch even in a slight degree, crevasses would in many instances be avoided in situations where they are found in abundance. As the ability of ice to stretch decreases with temperature, it is to be expected that in the far north the conditions are unfavorable for the study of such phenomena. On the whole, the observations thus far made on the breaking of glacial ice and the formation of crevasses, do not seem to controvert the results of experiments which show that ice does yield to slowly applied tension, without rupture. What has been shown by glacialists in many countries, is that the limit to which glacial ice can yield to tension under certain conditions is frequently exceeded. It was also noticed that boulders resting on the glaciers in Greenland, or inclosed within them, showed no tendency to descend through the ice as heavy substances descend through viscous bodies. This, as is well known, is true of boulders carried by glaciers in all countries, and offers an objection to the hypothesis of plasticity that cannot be easily removed.

Everywhere, as stated by Chamberlin, the ice of the Greenland glaciers appeared to behave as a rigid rather than as a plastic substance. The rigidity did not prevent contortions and foldings of the laminated ice, but faults and vein structure also occurred, and there seemed to be no more occasion to assume plasticity in the one case than in the other.

The same author also remarks "that there is a theoretical objection to the assumption of viscous flowage in the very fact of crystallization itself. The property of viscous flowage rests upon the relative indifference of a particle as to its special point of adhesion to its neighbor particles. The property of crystallization rests upon the strongest preferences respecting such relationships. Particles of water in their fluid condition lie against and cohere to each other indifferently. When they take on a crystalline form they arrange themselves in specific relationships by the exercise of a force of the highest order. In the presence of this very forceful disposition of the particles to retain fixed relationships to each other, it would seem little less than a contradiction of terms to attribute to them viscous flowage. The crystalline body may readily be made to change its form by the removal of particles from one portion by melting and their attachment at other points by congelation, but not, I think, by the flowing of crystallized particles over each other while in their crystallized condition."

While some of the objections to the hypothesis of plasticity advanced by Chamberlin are at present unanswerable, and his general conclusion in reference to the rigidity of the ice at the north of much weight, yet the theoretical considerations just quoted would seem to be more than counterbalanced by the experiments which show that ice composed of many crystals does yield continuously without fracture both to compression and tension. If a slab of ice supported at its ends does gradually sag under the influence of its own weight, simply, and at temperatures that do not admit of melting and refreezing, it seems unnecessary to argue that on account of its crystalline structure it is impossible for it so to yield.

The discussion that has been carried on for half a century respecting the hypothesis of plasticity has been ably advocated on each side, and some of the arguments against it remain unanswered; but to-day many able investigators, and especially many of those who are familiar with glaciers from actual contact with them, hold that it more nearly meets the required conditions than any other hypothesis that has been proposed. That it is not a complete and sufficient explanation of all the phenomena associated with the flow of glaciers, however, will appear still more forcibly, I think, from a review of other explanations that have been proposed.

The Hypothesis of Regelation. It is now well known, thanks to Faraday, Tyndall, and others, that when two pieces of ice having a temperature of about 32° F. are brought in contact they freeze together. This property, now termed *regelation*, was studied especially by Tyndall,

and by him first used in attempting to explain glacier motion. Under the hypothesis of regelation the ice of glaciers is thought to be crushed and the fragments reunited by refreezing after a change of position. "It is easy, therefore," says Tyndall, "to understand how a substance so endowed can be squeezed through the gorges of the Alps, can bend so as to accommodate itself to the flexures of the Alpine valleys, and can permit a differential motion of its parts without at the same time possessing a single trace of viscosity."

In illustration of the process of regelation numerous experiments have been made by placing fragments of ice in moulds of various forms, and subjecting them to pressure. When thus treated the ice is crushed and the fragments move past each other so as to take new positions, and are thus adjusted to the shape of the cavity containing them, but freeze together in their new positions and form a solid body. In this manner ice has been made to assume almost any desired shape. When the pressure is slowly applied rude fracture is avoided and the ice changes its shape in apparently the same manner as many plastic substances would if experimented with in a similar way.

In applying the principle of regelation to account for the flow of glaciers, it is assumed that the ice is crushed and that the fragments are made to move past each other and are refrozen in new positions. That rude fractures may be healed by regelation is abundantly attested. When a glacier passes down a steep descent it is greatly crevassed, but below such an ice fall the fissures frequently close, their walls freeze together, and the ice is possibly even more compact and homogeneous than before it was fractured. The conclusion, however, that the characteristic flow of glacial ice is accomplished in the same manner, but by incipient fractures, has been seriously questioned.

In the hypothesis of regelation, as in the hypothesis of plasticity, the force which causes motion is assumed to be the weight of the ice. Instead of flowing as a plastic substance, however, the ice is considered as behaving as a brittle substance, under the conditions to which it is subjected, and as being crushed and having the fragments reunited by freezing after a change in their relative positions. In all of the experiments that have been made to illustrate the process of regelation a force greater than the weight of the ice experimented on has been applied. Much discussion has been carried on in reference to the regelation of ice once fractured and having its fragments brought in contact at the proper temperature; but little has been said, however, in reference to the manner in which glaciers

might be crushed so as to make regelation possible. As has been shown by Moseley, a pressure of about 75 pounds per square inch is necessary to shear ice if applied with comparative rapidity. Although it seems impossible to apply these experiments in a quantitative way in explaining the movement of glaciers, they indicate that certain general conclusions may be valid. From the experiments referred to it has been computed that a column of ice in order to begin to crush at its base would have to be over 700 feet high. Evidently, then, glacier ice cannot be crushed under its own weight unless at least 700 feet thick, and then the fracturing would be confined to the bottom layer; we should, therefore, under the hypothesis of regelation, expect the greatest freedom of movement to occur in the basal position of a glacier. Yet, as is well known, the maximum movement is at the surface. How, then, can the principle of regelation be applied in explaining the surface flow, especially of a glacier with a low surface gradient? Again, regelation takes place at a temperature of about 32° F., and cannot occur much below that temperature unless the ice is under pressure. The rate at which the melting-point of ice is lowered by pressure is so small that practically it may be ignored in this discussion. Besides, the rate of surface flow of a glacier is greater than the rate below the surface, even in winter, when the temperature of the ice is frequently far below the point where regelation is possible. It seems, therefore, that the regelation hypothesis fails to meet several important features of the problem of glacier motion.

The principle of regelation is not to be entirely discarded in seeking an explanation of the behavior of glaciers, however, as the healing of fractures, as already noticed, may be satisfactorily explained in this manner. The principle of regelation apparently assists one in understanding how the granular snow of névés becomes consolidated under pressure into compact ice. As a névé becomes deeper and deeper, the granules of which it is composed, but which originate and increase in size from other causes, are brought in contact at the proper temperature and freeze together. The granules formed from light, porous snow may by this process be converted into compact ice.

It will undoubtedly occur to the reader that the question whether a glacier flows by reason of its plasticity or on account of fracture and regelation, could be decided by a study of the intimate structure of the ice of which it is composed. From a geological point of view glacier ice may be considered as a "rock" and investigated by petrographical methods. That is, it may be cut into thin sections and examined by means of the micro-

scope and polariscope. As already described, glacier ice has a peculiar *grain*, which is frequently so pronounced and characteristic that even a small fragment may in many instances be readily distinguished even by the unaided eye from lake and other ice. If the flow of glaciers is due to plasticity one would expect that the grain of the ice would exhibit something of a fibrous structure, similar perhaps in a general way to the structure of wrought iron, or to the structure of certain schistose rocks which have passed through a plastic condition. Nothing resembling this structure, however, is revealed in the grain of glacier ice. The structure of a characteristic sample of glacier ice, when examined by means of a polariscope, is shown in the accompanying figures,[1] one of which

A *B*

FIG. 10. — STRUCTURE OF GLACIAL ICE. (AFTER DEELEY AND FLETCHER.)

A two-thirds natural size. The section is vertical and at right angles to the direction of flow.
B natural size. The section is vertical and parallel with the direction of flow.

exhibits the appearance of a thin section cut parallel, and the other at right angles to, the direction of flow. Although the grains in the section parallel with the direction of flow are perhaps slightly flattened, nothing resembling a fibrous structure or a marked elongation of the granules is apparent.

Experiments by A. Heim,[2] have shown that the peculiar grain of glacier ice is accurately imitated when ordinary lake ice is crushed and again consolidated by regelation. So far as the study of the intimate structure of glacier ice bears on the explanations of glacier motion already considered,

[1] These diagrams are copied from a paper on "The Structure of Glacier Ice and its Bearing upon Glacier Motion," by R. M. Deeley and George Fletcher, Geological Magazine (London), Decade 4, vol. 2, 1895, pp. 152–162.

[2] "On Glaciers," Philosophical Magazine, vol. 41, 1871, pp. 485–508. Translated from Poggendorff's Annalen, Ergänzungsband, 1870, pp. 30–63.

it favors the hypothesis of regelation rather than that of plasticity. Yet, the observed uniformity in the size of granules composing glacier ice at various localities and their gradual increase in size from near the source of a glacier but below the lower limit of the névé to its extremity, are not accounted for on the supposition that continual crushing and refreezing take place.

The Hypothesis of Expansion and Contraction. — Geologists are familiar with the fact that talus slopes, as the piles of loose rock fragments at the bases of steep escarpments are termed, experience a slow downward *creep*, due to the alternate expansion and contraction of the fragments composing them, with changes of temperature assisted by gravity. In a similar way sheets of lead, as observed by Moseley, will slowly creep down an inclined surface when exposed to variations of temperature. Glacier ice is exposed to changes of temperature and subject to similar variations in volume, but owing to the fact that the same change of temperature will produce greater changes in ice than in rocks or lead, that is, owing to its greater coefficient of expansion,[1] its movements under the same fluctuations of temperature will be greater.

It is claimed by the advocates of the hypothesis under review, that in the case of an alpine glacier, for example, the ice in alternately contracting and expanding will slowly creep down a valley, since movement in that direction is assisted by gravity and in the opposite direction is opposed to gravity. The same argument has been applied, also, to continental glaciers originating on a plain and flowing in all directions from a center of accumulation, since on account of the rise of the surface gradient from the periphery toward the center of the mass, the weight of ice acting on any point in the glacier is greater in one direction than in others.

This hypothesis of alternate dilation and contraction was advanced by Moseley[2] and sustained by strong arguments and suggestive experiments, but has been severely criticised by Ball[3] and others. Among the objections suggested in reference to it are the following:

[1] The coefficient of expansion of ice is nearly twice that of lead, and more than twice that of any other solid.

[2] "On the Motion of a Plate of Metal on an Inclined Plane, when Dilated and Contracted; and on the Descent of Glaciers," Philosophical Magazine, Fourth Series, vol. 23, 1862, pp. 72–79.

[3] "On the Cause of the Descent of Glaciers," Philosophical Magazine, Fourth Series, vol. 40, 1870, pp. 1–10.

A glacier lying in a high-grade mountain valley or flowing from a center of accumulation on a plain, would, if it experienced changes of temperature, alternately contract and expand, and these changes in volume should produce a resultant motion in the direction of least resistance. The direction of least resistance at nearly all points in a glacier is upward, hence in general the movements in a glacier resulting from contraction and expansion would be in a direction normal to the surface of the ice.

The changes of temperature which might be expected to cause a glacier to "creep" are such as affect it below the melting-point of ice, for if raised above that temperature it will melt. Observations have shown that the internal temperature of glaciers is uniformly 32° F., but extended measurements in this connection, especially in winter, are wanting. We know, however, that so long as the interstices of ice are occupied by water the temperature of the mass cannot vary sensibly from that just stated, the effect of pressure being disregarded; and as glaciers, at least in temperate latitudes, are as a rule saturated with water in summer, they must have a uniform temperature at that season of 32° F. In winter the temperature of the air above a glacier may fall far below freezing, and if such a change should be continued long enough the temperature of the entire glacier would be correspondingly lowered.

With the above considerations in mind it is evident that under the "creeping hypothesis" the rate of flow of a glacier should be greater in winter than in summer, and should also be more rapid by night than by day. This seems to be a crucial test which reduces the hypothesis to an absurdity, since we know that glaciers flow more rapidly in summer than in winter, and that their motion is greater by day than by night.

If additional evidence of the inadequacy of the hypothesis of dilatation and contraction was desired, the slow conductivity of both ice and snow, and the manner in which glaciers are invariably blanketed with snow throughout a large part of the year might be considered. For example, in névé regions, the loose granular snow is frequently hundreds of feet deep, and is not only an exceedingly poor conductor of heat, but, on account of its open texture, would undergo but slight changes in mass on account of changes in temperature, since slight movements of the granules would be taken up by the adjacent interspaces. It does not require accurate observations to show that in such regions changes of temperature are too brief to be felt at any considerable depth, and even under the most ex-

treme conditions could not cause sufficient change to account for the flow known to occur in névés. The considerations here suggested will be again referred to in connection with certain "molecular hypotheses" that have been proposed to account for glacier flow.

From the considerations offered above it seems evident that the hypothesis suggested by Moseley cannot be accepted as a final explanation of the flow of glaciers.

It is equally plain, however, that it does contain an element of truth, since it cannot be denied that ice, like most other substances, does contract and expand with changes of temperature, or that glaciers are exposed to conditions which bring about such changes. Some fraction of glacier motion must, therefore, be due to those causes.

The Hypothesis of Liquefaction under Pressure. — The fact that the freezing-point of water is lowered by pressure, discovered by James Thompson[1] and confirmed by his brother William,[1] was at once applied in explanation of glacier motion.

As stated in the papers just referred to, if ice at 32° F. is subjected to pressure, pores occupied by liquid water must instantly be formed in the compressed parts, for the reason that ice cannot exist at the above temperature under a pressure exceeding one atmosphere. If the conditions permit, the water formed by the melting of the parts under pressure will be forced to where the pressure is less and at once refreeze. The parts recongealed after being melted must in turn, through the yielding of other parts, receive pressure from the applied force, thereby to be again liquefied and to enter again into a similar cycle.

In applying this principle to glaciers it is claimed that the water formed by liquefaction may in part descend, and on refreezing occupy a lower position. (It might be asked, however, why the water, if under pressure, should descend rather than move in any other direction.) A continuation of this process, it must be admitted, would *tend* to crowd an alpine glacier down the valley it occupies, but the amount of movement thus produced would be small.

In opposition to this hypothesis it is evident that the greatest pressure, at least in the case of a glacier flowing through an even channel, is at the bottom, while the surface sustains the pressure of only one atmosphere,

[1] "On the Plasticity of Ice, as manifested in Glaciers," Roy. Soc., Proc., vol. 8, 1857, pp. 455–458. "On Recent Theories and Experiments regarding Ice at or near its Melting-point," Roy. Soc., Proc., vol. 10, 1859, pp. 152–160.

and in the great majority of cases of less than one atmosphere, yet the maximum flow is always at the surface. Additional weight is given to this objection when we recall the fact that the flowing motion observed in glaciers is greatest at the surface even in cold weather; at such times the surface ice may reasonably be concluded to have a lower temperature than the bottom ice, and therefore require a greater amount of pressure to cause it to liquefy.

It does not seem as if further argument was necessary to show that the lowering of the melting-point of ice by pressure does not furnish a complete and satisfactory explanation of glacier motion ; but that it may play a part in the phenomena for which an explanation is sought, especially in the case of excessively thick ice bodies or of glaciers flowing through irregular channels, cannot be refuted.

The Hypothesis of Molecular Change. — An ingenious and highly suggestive hypothesis advanced by James Croll to account for the flow of glaciers is based, in part, on the well-known fact that water in freezing gives out heat and expands on passing to the solid state ; and conversely, when ice melts heat is absorbed, and in passing to the liquid state occupies less space than before the change. The difference in volume between ice at 32° F. and the water formed from its melting, at the same temperature, is about one-tenth, that is, the ice occupies one-tenth more space than the water.

Another principle that enters into this hypothesis is that heat above 32° may be transmitted through ice, and yet the ice as a mass remain solid. This has been demonstrated by Tyndall and others by placing a delicate heat-measuring apparatus on one side of a slab of ice and bringing heat to the opposite side. It may thus be shown that some of the heat will pass through the ice, but portions of it are retained and produce changes within the mass. As demonstrated by Tyndall, in producing "liquid flowers" in ice by passing heat through it, a portion of the interior of the mass of ice may be melted by heat that passes through other portions which remain solid.

The hypothesis before us assumes that the heat of the sun on reaching the surface of a glacier is partially expended in melting its surface, and that a part of the water thus formed is transferred to the ice below and is refrozen, and that the heat liberated melts other portions, which again refreeze, and so on. The essential feature of the hypothesis is that the heat which enters the ice directly also leads to molecular changes, which cause the ice to descend. Molecules of ice are assumed to be melted, and on

refreezing pass their heat to other molecules. But the molecules liquefied occupy less space than before melting and change their position in response to gravity or pressure, and on refreezing again expand and exert a force on their confining walls.

In the hope of stating this hypothesis more definitely I will use Croll's own words: "Let us observe what takes place, say, at the lower end of the glacier. A molecule *A* at the lower end, say at its surface, receives heat from the sun's rays; it melts and in melting not only loses its shearing force and descends by its own weight, but it contracts also. *B*, immediately above it, is now, so far as *A* is concerned, at liberty to descend, and will do so the moment that it assumes the liquid state. *A* by this time has become solid and again fixed by shearing force, but is not fixed in its old position, but a little below where it was before. If *B* has not already passed into the fluid state in consequence of heat derived from the sun, the additional supply which it will receive from the solidifying of *A* will melt it. The moment that *B* becomes fluid it will descend till it reaches *A*. *B* then is solidified a little below its former position. The same process of reasoning is in a similar manner applicable to every molecule of the glacier. Each molecule of the glacier consequently descends step by step as it melts and solidifies, and hence the glacier, considered as a mass, is in a state of constant motion downwards."

The heat that reaches a glacier, as stated by Croll, is (1) from the sun, either directly or through the medium of the atmosphere, rain, etc.; (2) earth-heat from the rocks over which the glacier passes; and (3) the heat produced by friction. Of these, it seems to the present writer, account need only be taken of the heat derived from the sun. The earth-heat is certainly small, and for the present at least can be considered as having no practical bearing on the question in hand. The heat of friction, if the movements of a glacier are caused solely by the molecular changes considered by Croll, is due to the arrest of motion produced by the energy of the sun, and to admit it as a source of energy to be used in explaining glacier movement would be utilizing the same energy twice. That is, if the sun's heat produces glacial movement, and by the arrest of this movement a part of the energy which caused it is reconverted into heat, which in its turn causes glacial motion, there is no end to the circle. A glacier would then be an example of perpetual motion.

The above is confessedly an imperfect statement of the molecular hypothesis, and it is perhaps unjust to suggest obstacles to its acceptance without a more complete presentation, but as space will not admit of this,

I must refer the reader to Croll's papers and books for a full exposition of his case.[1]

Neglecting the purely theoretical discussion of the manner in which the molecules of ice are supposed to be influenced by the passage of heat through it, since this is a question for physicists, let us, as geographers, see how the hypothesis before us meets the actual conditions with which we are familiar from field observations.

Assuming, what must be practically true so far as this hypothesis is concerned, that all the heat which reaches a glacier comes from the sun, it follows that the energy requisite to loosen the molecules of the ice and to allow gravity to act in the manner postulated, can only be transmitted to the glacier when a thermometer at its surface at the point where the heat enters stands above 32° F. The higher the temperature indicated by such a thermometer the more rapid would be the ice movement. Also, from the fact that a large amount of energy is consumed in changing the molecular condition of ice before it can melt — physicists tell us that the amount of heat absorbed by ice at 32° F., in changing to water at the same temperature, is equal to the amount of heat required to raise the water thus formed from 32° F. to 172° — it follows that a thermometer at the surface of a glacier would have to rise well above 32° F. or remain somewhat above that temperature for a considerable time in order that the ice might receive the requisite amount of heat to initiate the process described by the author of the molecular hypothesis.

In attempting to apply this hypothesis, however, we are met at the outset with the conclusion, not yet successfully controverted, that the internal temperature of a glacier is always 32° F. or lower. This conclusion is based on several facts, as for example: first, direct observations show that as nearly as can be determined the internal temperature of a glacier in summer is 32° F.; second, ice in melting under atmospheric pressure changes to water with a temperature of 32° F., and a mixture of ice and water has this temperature; third, a mass of ice in contact with air below 32° F. will have its temperature lowered.

Turning now to a typical alpine glacier we find that near its source the temperature of the air in contrast with it is always low. In the Mount St. Elias region surface melting does not occur at elevations in excess of about 13,000 feet. Above that elevation the snow is always light and dry.

[1] "On the Physical Cause of the Motion of Glaciers," Philosophical Magazine, vol. 38, 1869, pp. 201–206. "Climate and Time," 1875, pp. 1166–1195. Also, "The Great Ice Age," by James Geikie, 2d ed., 1877, pp. 21–31.

At noon on a cloudless August day, at an elevation of 14,000 feet on the side of Mount St. Elias, I found the temperature of the snow at a depth of two or three inches, where the surface was directly exposed to the sun, to be sixteen degrees below freezing. This, it must be remembered, is the most favorable condition for melting that occurs throughout the entire year at the locality referred to. At night, even in summer, the temperature of the air falls far below freezing. For probably nine months or more each year the temperature of the snow at the surface of the névés in the St. Elias region is continuously below the freezing-point. It is impossible to see how under these conditions the molecular hypothesis can be applied, yet it is in regions of the nature referred to that glaciers have their birth. The snow accumulating on névés must move downward before trunk glaciers can be formed, but if the flow of the lower portions of glaciers is to be accounted for by molecular changes the same explanation should be applicable to névé regions as well.

In some respects the impressions conveyed by what is stated above will be incorrect, for the reason that few névés are so circumstanced that melting does not occur on them during a portion of each year. I shall endeavor to show, however, that the other extreme of conditions to which névés are subjected is no more favorable to the molecular hypothesis. As is well known, the surfaces of névés for a large part of each year are composed of light, dry snow. The consolidation of this snow, it would seem, must take place before a pushing force of the nature postulated by Croll could act efficiently in producing a flowing movement in the mass. Consolidation of névé snow does not occur when the temperature of the air in contact with it is above the freezing-point, as it is then partially melted and frequently so completely saturated with water as to be soft and slushy, and, many times, holds shallow lakes in depressions of its surface. No one will claim, I fancy, that a mixture of snow and water of such a consistency that one will sink knee-deep into it at every step — a condition frequently present on the névé of Alaska — is favorable to the passage of heat through it so as to produce molecular changes in the ice below.

It appears, then, that the surface of a névé, both when below 32° F., or when it is open and porous, and when it is exposed to a greater temperature and becomes saturated with water, is unfavorable for the transmission of solar energy. Again, the surface of a névé is renewed each winter, and in many instances by summer storms as well; and at such times is at 32° F. or lower; and when surface melting is in progress the snow is saturated with water and consequently has a temperature of 32° F., hence it is impossible

to conceive how a temperature in excess of 32° F. could be transmitted to the solid ice beneath so as to give it motion.

Nor are the difficulties in the way of applying the molecular hypothesis confined to névé regions. The portion of a glacier that protrudes below its névé is blanketed with snow in winter; the air in contact with it is then, also, normally below freezing. In summer the surface of the ice is frequently covered with a porous, coral-like crust, which is almost as perfect a non-conductor as dry snow; and when this crust is in process of melting it is saturated with water and consequently has a general temperature of 32° F., and will not allow heat in excess of that temperature to pass. Glaciers are also frequently covered more or less completely with moraines, which, when over a few inches in thickness, still more effectually shield the ice beneath from solar energy. When we consider the nature of the surface presented by a glacier from its clear-white, snow-covered névé to its dark and frequently moraine-covered terminus, it is apparent that the positions where hard, blue ice is exposed to the sky are relatively few. It may be said in general that clear ice is only exposed for any considerable time when its surface gradient is sufficient to insure the quick escape of the water formed by superficial melting. Under the molecular hypothesis, other conditions being the same, motion should be most rapid where the surface of a glacier is composed of clear ice. So far as now known observations do not harmonize with this postulate.

Although heat may be transmitted through ice in laboratory experiments and cause melting within its mass, yet the conditions, as shown above, when this can occur in the case of glaciers are so infrequent that the application of this principle in explanation of glacier motion, even if we knew the nature of the molecular changes that occur, meets what seem insuperable difficulties.

The Hypothesis of Granular Change. — Recent observations on the structure of certain Greenland glaciers by T. C. Chamberlin[1] have led him to conclude, as previously noted, that they behave as rigid rather than as plastic bodies. The impression gained was that the ice is thrust forward by an expansive force acting from within rather than pulled by gravity alone after the manner of plastic substances. In seeking for an explanation of glacier flow with this idea in mind Chamberlin again directed attention to the changes which occur in the granulation of glacier ice when traced from its source to the extremity of a glacier, and, as others

[1] "Recent Glacial Studies in Greenland," Geol. Soc. Am., Bull., vol. 6, 1895, pp. 199–220.

have done, suggested that the principal cause of movement may lie in the growth of the granules. Through a process of partial melting and refreezing it is assumed that a granule may continually change its shape by loss in one part and gain in another, and thus either move itself or permit motion in a neighbor. To bring about this change the author states that "every warm day sends down into the glacier a wave of heat energy, sensible or potential, and that every night sends after it a wave of reverse energy. These waves follow each other indefinitely, until by intercurrent agencies they become vanishing quantities. Each season sends through the mass a greater and more complex wave. The problem, therefore, in simplified form postulates a mass of ice granules predisposed to melt at certain points and to freeze or to promote freezing at others, acted upon by the ever-present but differential force of gravity and swept by successive waves of heat energy competent to cause melting where predisposition to melting exists and to cause growth by freezing where predisposition to freezing exists. Out of this it would seem that localized freezing and thawing, growths and decadences, innumerable and constantly changing, must result, and with them motion of the granules themselves and of the common mass."

Although, in fairness to my readers, I must confess that I am unable to discuss either the molecular hypothesis or the recent modification of it from the standpoint of the physicist, yet the adverse bearing of certain facts on these hypotheses and difficulties in the way of applying them to explain well-known glacial phenomena suggest themselves even to a layman.

Present knowledge of the physical properties of ice and of water seems to show that when they are in contact at the same temperature, at least when not under pressure exceeding one atmosphere, there is no reason to suppose that there would be a mutual change of condition. That is, so far as I am aware, there is no reason to suppose that a molecule of water at 32° and a molecule of ice at the same temperature, placed side by side, would undergo a mutual interchange of their physical properties, the water becoming ice and the ice changing to water. But this seems to be an essential feature, although not stated in these words, of both the molecular hypothesis and the modified version of it.

Another consideration is that molecular changes postulated cannot take place in ice that is below 32° F. unless pressure is greatly increased. If pressure is the controlling condition, then the movements supposed to occur would increase with depth of ice, and the bottom of a glacier should flow

more rapidly than its surface. This, we know, is the opposite of what really does take place.

Chamberlin speaks of waves of sensible or potential heat energy passing through a glacier every warm day, but it is to be remembered that warm days on the upper portions of glaciers, especially, are rare ; and, as already pointed out, the névé of a glacier is constantly blanketed by a non-conducting layer such as no wave of sensible heat, at least, can penetrate.

The explanation suggested by Chamberlin, like its predecessor, is based on theoretical deductions which have not been proven. Before claiming that solar energy causes motion in glaciers by the melting and refreezing of molecules, or by changes in the size and shape of granules, it would be more consistent to determine if these changes do occur in ice under the most favorable conditions. But even if it could be shown that a "wave of heat energy, sensible or potential," could lead to a change in the form and size of granules, the same objections to the transfer of such energy from the surface to the inner positions of a glacier, suggested in reference to Croll's hypothesis, would have to be met.

While it is apparently impossible to demonstrate that the changes in ice assumed by Croll and Chamberlin do not take place, it is logical to wait until sufficient reasons have been advanced to prove that they do occur even under the most favorable conditions, before making the assumption the basis of a still more extended hypothesis. At present the postulates on which the molecular hypothesis and its recent modification rest, may be said to be in the hands of the physicist. If their truth is ultimately demonstrated, they may be passed on to the geologist and geographer to be tested as a means of explaining glacial motion.

What seems intended as a modification of the molecular hypothesis has been proposed by R. M. Deeley[1] and can be studied with profit, but so far as I have been able to determine it does not differ materially from the explanation proposed by Croll.

Conclusion.

From the brief account given above of various hypotheses that have been advanced to account for the movements of glaciers, it will be seen that no one of them meets all the conditions of the problem. No one explanation has been generally accepted, although the hypothesis of plas-

[1] "A Theory of Glacial Motion," Philosophical Magazine, vol. 25, 1888, pp. 136–164.

ticity probably has more adherents than any other. From what has been stated, however, I think it will appear that several of the explanations offered are based on one or more well-established laws and furnish an explanation of some phase of glacial motion. Even the earliest and long-since abandoned hypothesis of Charpentier, which assumes that glaciers slide as rigid bodies over their beds, contains, as we have seen, an element of truth. If this can be said of the crudest of all the explanations advanced, the later and more elaborate hypotheses should certainly not be discarded without careful scrutiny in order to obtain from them all the assistance in arriving at a final theory that is possible. To the discredit of men of science, it must be acknowledged, that in discussing the problem of glacier motion, the practice has too frequently prevailed of rejecting all previous hypotheses in order to make room for some newer idea. The attitude of scientific men in this connection has frequently been that of an advocate pleading for his client, rather than a judicial balancing of evidence.

An Eclectic Hypothesis. — The review just attempted leads to at least one conclusion which seems well founded. That is, the phenomena to be accounted for are complex, and no single law governing the behavior of ice can be made to explain all phases of glacier motion.

The principal laws and the leading physical properties of ice which are concerned in modifying the form of glaciers at one time or another, or at one locality or another, may be briefly enumerated as follows:

1. Gravity is ever present and tends continually to change the form of a glacier. This fundamental fact is recognized in every hypothesis that has been advanced.

2. Ice, although brittle under a force quickly applied, yields continuously under its own weight to both pressure and tension in a diminishing ratio from 32° F. to lower temperatures.

3. Fragments of ice when brought in contact at or near a temperature of 32° F. will freeze together, but without pressure this does not occur at lower temperatures.

4. Water expands on freezing, the increase in volume being about one-tenth. The converse is also true.

5. Water held in fissures or in the interstices of glaciers exerts a hydraulic pressure, and obeys the laws governing capillary attraction.

6. Ice like other solids expands and contracts with changes of temperature.

7. Heat can be made to pass through ice, as shown by Tyndall, and portions of the ice may be melted by heat that has passed through other portions without producing visible changes.

8. The melting-point of ice is lowered by pressure.

9. A mixture of ice and water under a pressure not exceeding one atmosphere has a temperature of 32° F.

10. Ice on melting absorbs heat. Water on freezing gives out heat.

11. The temperature of ice is raised by compression and lowered by tension.

Other laws may be added to this list, but at present those enumerated seem to be the principal ones that can be applied in solving the question of the causes of glacier motion.

The phenomena exhibited by glaciers for which explanation is sought may also be briefly enumerated:

1. Glaciers exhibit a well-defined flowing movement, analogous to the flow of plastic substances.

2. The flow of a glacier, best illustrated by one of the alpine type, is greatest in the center and at the surface, and decreases toward the sides and bottom. That is, it is analogous to the flow of a river.

3. The flow is greater in summer than in winter, and greater by day than by night. That is, it varies in harmony with changes in atmospheric temperature, and is greatest when the temperature is highest. More than this, observations have shown that changes in the rate of flow respond with considerable promptness to changes of temperature.

4. The movements of any given point in a glacier are not uniform in any one direction, but vary from hour to hour. In the case of an alpine glacier so far as has been observed, the algebraic sum of the movements by day are in the direction of descent, while at night there may be a resultant displacement toward the mountain from which the glacier flows.

5. Motion occurs both in névé regions and in the glacier proper, and so far as known is of the same nature in each instance; but more extended studies in this connection are desired.

6. The mean rate at which a glacier flows is not the same in different portions of its course. That is, for example, the average rate of movement of all points in a given cross section may vary widely from a similar average in another cross section.

7. When the grade of a valley through which a glacier flows changes abruptly, or when its bottom or sides are markedly irregular, the ice becomes broken and crevassed. Tension is also produced under other

conditions, as when a glacier expands on a plain, and fissures are again formed.

8. Glacial ice abounds in fissures and interstices which are usually filled with water. Near the surface the water held in this manner frequently freezes at night. The effect of winter temperatures must be felt to a still greater depth, but how deep has not been determined. Water flows from beneath the extremity of nearly every alpine glacier, even in winter, and to a great extent represents the drainage of the ice. Evidently the fall of temperature in winter is not sufficient, or not long enough continued, to congeal all the water that enters the ice during the summer season.

9. Glacial ice is granular. Névé snow is also granular. As shown by Heim, however, the granules of the névé are distinct and of a different nature from the granules of glacier ice. In the glacier proper the granules increase in size from near the névé to its extremity. In restricted areas the granules are of approximately the same size, large and small grains not being intermingled.

10. When glacial ice is broken, as when crevasses are formed, and the fragments brought in contact, they refreeze.

11. The rocks over which glaciers move become worn and striated. Hard nodules in glaciated rocks are frequently left in relief. "Chatter marks," semi-lunar cracks, etc., also occur on surfaces but recently abandoned by a receding glacier.

12. Rock basins but recently vacated by glacier ice are smoothed and striated within, showing that débris-charged ice descended into them so as to wear their surfaces.

13. Débris contained in a glacier tends to decrease its rate of flow. If we conceive of a glacier compound of clear ice moving at a given rate and introduce débris — earth, sand, stones, boulders, etc. — into it, without altering other conditions, the effect will be to decrease the rate of flow, since rigid substances are added to one having properties that are at least analogous to those of a plastic solid. If we gradually increase the percentage of débris, the mass will become less and less mobile, and finally acquire such rigidity that under the conditions normally influencing the movements of glaciers it will cease to flow. If the débris, instead of being uniformly commingled with the ice, is introduced irregularly, local changes in the rate of flow and even local stagnation will result.[1]

[1] The influence of débris on the flow of glaciers, based on the assumption that ice is plastic and when in sufficiently large masses will flow under the influence of its own weight, has been discussed by the author in The Journal of Geology [Chicago], vol. 3, 1895, pp. 823–832.

This list of facts, bearing more or less directly on the character of the movements that take place in glaciers, and thus furnishing data for testing proposed explanations of their movements, might be extended, but I believe that the most suggestive observations now in hand have been enumerated.

By codifying the laws governing the behavior of ice under various conditions, and grouping the phenomena related more or less directly with glacial flow, in the manner just attempted, it will appear, I think, that the movements of glacial ice are more complex than has commonly been stated, and are due at different times and under different conditions to different agencies, or to the interaction of various agencies.

Of the forces to which glaciers are exposed which tend to change their shapes, gravity is the only one that acts continually and always in the same direction. The fact that ice, as shown by careful experiments, will change its shape under the influence of its own weight at all temperatures from a maximum rate at 32° F. as far below as tests have been carried, and yields continuously to tension as well as to pressure, is strong evidence favoring the assumption that glaciers descend or flow in a manner analogous to the flow of plastic bodies. Supplementing this cause of glacier motion, although apparently in most instances of minor importance, is the hydrostatic pressure of water enclosed in glacial ice; dilatation of water in freezing in fissures; expansion and contraction of the ice with changes of temperature; melting and refreezing, due to changes in pressure; regelation; and, less clearly, molecular changes caused by the transmission of heat, and the melting, refreezing, and growth of granules.

The authors of this eclectic hypothesis may be considered to be De Saussure, Charpentier, Agassiz, Forbes, Rendu, Guyot, Tyndall, Thompson, Croll, Geikie, Heim, Helmholtz, Moseley, McConnel, Chamberlin, and in fact all physicists and glacialists who either directly or indirectly have contributed to the study of glacial dynamics. More than this, the study of the physical properties of ice and the application of principles already known or to be discovered in explanation of glacier movements, is not yet completed. To the list of distinguished names given above, as the authors of the "eclectic hypothesis," are to be added the names of those who in the future make contributions to our knowledge of the properties of ice and of its behavior under various conditions. The new facts and new principles discovered are to be included in this hypothesis, which will thus continue to be an illustration of the evolution of ideas.

CHAPTER X.

THE LIFE HISTORY OF A GLACIER.

GLACIERS, like streams and lakes, valleys and mountains, have their periods of youth, adolescence, maturity, and old age, leading to extinction. Like the snows of winter they come and go in obedience to unseen forces. Their growth and decline may embrace thousands and even tens of thousands of years, but even the longest-lived witness but a portion of the changes in topographical development to which they lend their aid. The study of existing ice bodies leads backward step by step to the far greater ice sheets of the glacial epoch. Although the causes that produced vast continental glaciers in comparatively recent geological times are not well understood, and have been a fruitful source of controversy, yet when one has in mind the life history of a single existing glacier, it becomes evident that former periods of extensive glaciation were but greater steps in the same direction. Methods of study are thus indicated, and suggestions obtained for attacking unsolved problems in the history of the earth.

As a beginning in this broad field of exploration, let us endeavor to obtain a graphic idea of the changes made manifest in the birth, growth, decline, and death of a single alpine glacier.

The snow line — the lowest limit of perennial snow — may be said to have its position determined by the intersection of the earth's surface with an invisible, hollow spheroid of temperature. This invisible spheroid may for present purposes be fancied to pass through all points having a mean annual temperature of 32° F. In the tropics it is some 18,000 feet above the sea, but decreases in elevation toward either pole. In high latitudes, it may pass below the earth's surface. Its size and form change in obedience to many far-reaching and frequently antagonistic agencies, and is never the same for two consecutive years or for any two terms of years that may be selected. It is modified from within by changes in the inherent heat of the earth, in movements producing elevations and depressions, in the distribution of land and water, in the direction and character of ocean currents, in the movements of the atmosphere, in the distribution of vegetation, in topographic relief, and in other

ways. It is modified from without, principally by annual and secular changes in the amount of heat that reaches the earth from the sun due to changes in the position of the earth, the inclination of the earth's axis, and perhaps other causes.

When one endeavors to marshal in fancy the interaction of the various conditions on which the fluctuations of the snow line depend, the wonderful complexity of glacial problems is suggested. The difficulties to be overcome are still farther increased when one recalls the fact that while glaciers do not originate when the mean annual temperature is above 32°, they may not form when that limit is reached, unless still other conditions, as an abundance of snow, alternations of warm and cold seasons, etc., are fulfilled.

Could we tint the ever-changing surface of the spheroid of 32° as the student who uses the microscope sometimes tints the walls of the cells he examines, and view the earth from a distance, its pulsations in obedience to the many forces on which its size and form depend would be manifest. Under those conditions, were time allowed, the various steps in the gathering of perennial snows, the birth and growth of glaciers, and the coming and going of geological winters could be followed.

This fancied view of the working of a single part of the complicate machinery we term climate, is not intended to lead to a discussion of the ultimate causes of glacial conditions, but merely to invite the reader to cut loose from ideas of days and years, and view the growth and decline of a glacier which numbers centuries in its life-span.

The histories of the three main classes of glaciers usually recognized are not the same but have many features in common. Individual examples of each class require such a length of time to run their appointed courses, that but a faint idea of the changes they undergo can be gained from the study of a single example, even if one spent an average lifetime in the task. But by combining observations, made in various regions, on glaciers that have reached different stages in their development or decline, the chief episodes in the life history of a typical example may be outlined. Let us climb to a station on a mountain-side, overlooking a deep valley that leads from white peaks above to a dark, forest-covered plain below, and watch in fancy the birth, growth, and retreat of a single glacier of the alpine type.

The life of an alpine glacier usually begins when a mountain summit pierces the spheroid of 32°. Whether this happens on account of changes in the lithosphere or in the spheroid of temperature, or by

a mutual adjustment of the two, is beyond our present theme. As the mountain peak reaches higher and higher above the spheroid of 32°, the mantle of snow drawn about its summit descends lower and lower. Above the snow line the winter's snow is not completely melted during the succeeding summer, and accumulates from year to year. If the mountain was sculptured by streams before the postulated change occurred, or is irregular for other reasons, the snow will be blown from the peaks and ridges and accumulate to a great depth in the depressions. The head of a valley becomes filled in this manner with a broad snow field, and in summer the mountain seems to be tipped with silver. The snow toward the bottom of the accumulation becomes consolidated by pressure. Water formed by surface melting percolates through it and is frozen. The lower layers are thus changed to ice, and a névé is born. The surface of the snow field is softened and partially melted during days of sunshine or when warm winds blow over it, and freezes at night or during storms, and a thin crust of ice is formed. This hard, glittering layer is buried beneath the next succeeding snowfall, and remains as a well-defined stratum in the growing névé. In the walls of crevasses, the thin sheets of ice formed in this way, as may be learned from a near inspection, appear as narrow blue bands separating layers of snow, perhaps many feet thick. Dust blown from adjacent peaks and cliffs that rise above the névé, stains its surface. The discolored layer is buried beneath subsequent snowfalls, and again accents the stratification of the deposit.

If we could plant a row of signals across the névé at right angles to the trend of the valley down which its surface inclines, we should find in the course of a few days, or even in a few hours, if our observations were sufficiently refined, that there is a slow surface movement, greater in the central and lower portion and tending down the valley. Could we make similar measurements in a vertical direction where the surface movement is greatest, we should find that the maximum flow is below the surface, and probably near the bottom of the deposit. That the rate of movement increases with the depth and reaches a maximum near the bottom, is only an inference from the study of superficial phenomena, and has never been proven by direct measurements. In the glacier proper the threads of most rapid flow are known to be at a higher level in reference to the basement layer than is supposed to be the case in the névé; accompanying this apparent change in the position of the line of greatest movement are important modifications in the behavior of the flowing body.

The surface snow of the névé is carried along by the more rapid movement of the consolidated portion deep below, and great breaks are formed at the base of the encircling cliffs owing to the surface snow being moved away from them. These breaks, in which the rocks beneath are frequently exposed, are conspicuous from a distance. As we watch the slow growth of the glacier, we note in the course of centuries, that the amphitheatre from which it flows becomes gradually enlarged, its walls at the same time increasing in steepness. The great crevasses on the upper border of the névé are filled each winter, but reopen each spring in about the same places. Observations at intervals of centuries, however, would show that their positions do not remain the same, but owing to the waste of the rocks exposed each summer within them, a slow migration toward the crest of the mountains takes place, that is, the cliffs recede.

As the névé increases in thickness, the motion of the deeper layers becomes greater, and at length, in late summer or early autumn, a protrusion of solid ice is seen extending out from beneath its lower margin. The flow of the young glacier in some instances is so energetic that the névé field from which it is fed is seemingly in danger of exhaustion. At times, comparatively insignificant névés supply ice bodies that are disproportionately large. This occurrence seems to accompany climatic conditions that are unfavorable to surface melting. Possibly the workings of natural laws in this connection are better illustrated by young glaciers than by more aged examples, and more perfect snow drainage is secured than when the ice stream below becomes congested and is clogged with morainal material.

The young glacier advances its extremity by reason of the more rapid rate of flow of the ice near the surface and in the center of the stream. In this way, what was the expanded margin of the ice foot at any indicated time, becomes covered by the ice thrust forward during the next period of marked advance. The movement being greatest in summer and least in winter, there is an annual pulsation of the slowly advancing extremity. There are, besides, periodic changes of similar character but of greater magnitude. When the advance of the extremity of the glacier is rapid, the onward surface flow each summer buries the portion remaining from the previous summer advance. Débris carried on the surface of the glacial stream thus becomes transferred to the bottom layer. Moraines deposited in front of the advancing glacier during one summer become buried by the advancing terminus during the next succeeding summer, and are added to the ground moraine. Like results follow also from

similar periodic changes of greater magnitude. Owing to the manner of its advance, the terminus of a young glacier is steep. The frontal slope is generally higher and bolder than during old age, when the terminus is receding, but this is not always the case.

From our fancied station overlooking a valley down which a young glacier has begun its journey, and where also in fancy centuries are but as hours, we see other similar streams of ice descending tributary valleys and entering the main avenue of drainage.

The roar of avalanches, especially after heavy snowfalls, as they plow their way down the mountain-side, awakens the echoes as if heavy guns had been discharged. The rushing snow masses carry with them dirt, stones, and occasionally large rock masses, and assist in the formation of lateral moraines along the borders of the glaciers. When an interval of sunshine loosens the icy bands with which the shattered cliffs are bound, stones break away and join the rubbish piles below. Again, when the shadows of evening fall on the cliffs and the temperature is lowered below the freezing-point, additional blocks of stone pried off from the faces of precipices are shot downward with a shrill, whistling sound, and bury themselves in the soft snow below or strike with a dull thud on the hard ice. We can see many localities where the ice and snow adjacent to the cliffs has been melted back by the heat reflected from the rocks, and a deep gulf formed, into which stones falling from above are precipitated, and injected, as it were, into the body of the glaciers. There forbidding recesses, black with accumulated débris, are filled and buried by subsequent snowfalls. The waste from the cliffs is thus at the start sealed up in the borders of the flowing ice stream. Much of the morainal material, when it begins its slow, downward journey is thus inclosed in the snow and ice, or is englacial. It becomes superglacial far down the glacier, when the matrix melts and the foreign bodies contained in it are concentrated at the surface.

The ice streams advancing down lateral valleys, each in its youth a separate and independent glacier, unite on reaching the main channel and form a single compound stream. The various branches do not lose their identity and mingle as do the waters of confluent rivers, but with some change of form flow on side by side. This is plainly shown by the behavior of the marginal moraines on the adjacent borders of two glaciers after they unite. The two lateral streams below their point of union form a single medial moraine in the central part of the compound stream. While the lateral moraines are apparently united, they still retain some-

thing of their individuality. The material of which they are composed is not at first commingled, but continues as separate streams, flowing side by side. If one glacier is fringed with fragments of white quartzite, for example, and its neighbor with blocks of black basalt, the compound medial moraine below their place of union will be white on one side and black on the other. Such a division of a medial moraine may sometimes be noted many miles below the place where two tributaries unite. On highly compound glaciers the medial bands sometimes exhibit a score or more of individual threads.

At the extremity of each of the younger glaciers we have watched advancing there has been an arch in the ice, from beneath which a stream of muddy water flowed out. Each glacier is the source of a stream, and in some instances discharges a swift, roaring torrent having the volume of a river. These streams pulsate with the change of seasons. Their volume increases in summer and diminishes in winter. Winter and summer they are heavily charged with silt and mud, while the streams with which they unite, lower down the mountain, where there are no glaciers, are clear except after rains. Evidently the glaciers are wearing away the rocks over which they move, and the streams flowing beneath them are carrying away the finer products produced by the ceaseless grinding. The young glaciers conceal their work, and we must wait until they grow old and melt away before we can discover what changes are taking place in the channels through which they flow.

Our glacier now receiving the tribute of many lateral ice streams has passed from the youthful stage to maturity. It fills the valley at our feet from side to side, and is prolonged for many miles below the shining snow fields from beneath which we watched it emerge. The vast river of ice has a depth of a thousand feet or more and a breadth of perhaps one, two, or three miles. Its width is less than the united breadth of its many branches. Its great thickness is due to the lateral compression of the tributaries that have contributed to its growth.

The distinction is well marked between the clear white névé where the surface is renewed each year by fresh falls of snow, and the black and dirt-stained ice of the glacier proper, where waste exceeds supply and previously englacial material is being concentrated at the surface. The glacier proper, as well as the névé, is snow-covered each winter and the details of its surface blotted out, but with the return of summer the snow on the lower portion is entirely melted. The fringe of the snow mantle with which the mountains are covered is withdrawn higher and higher as

the warm season advances, until in late summer or early autumn, just before the first storms of the next succeeding winter begin, it reaches its maximum elevation. The true limit between the surface of the névé and of the glacier proper is then revealed. The snow line is higher on rock surfaces than on glaciers, showing that the dark rocks absorb more heat and melt the snow resting on them more thoroughly than does the brilliant ice. In our watch of centuries we note that the snow line experiences many fluctuations. As the glaciers increase in number and in size and their névés broaden, the snow line descends lower and lower, even though the general climatic conditions remain sensibly the same. This is on account of the reaction on the atmosphere of the ice bodies previously formed. The snow and ice-covered mountains chill the winds blowing over them more than formerly, and cause heavier precipitations. Each storm that sweeps over the white peaks, even in summer, is now accompanied by a fall of snow. Glaciers thus tend to change their meteorological environment in such a way as to favor their own growth.

The trunk glacier in the valley below continues to advance century after century and increases in thickness, particularly towards its terminus. In its middle and upper course, and especially in the névé region, the depth of the frozen flood is but little greater than during the earlier centuries of its maturity.

An increase in the thickness of a glacier which flows from a lofty mountain while due mainly to a decrease in the gradient of the valley it occupies, is aided also by an increase in the load of débris it carries. Each of these changes tends to increase the friction of flow, but as the advance of ice from above is continuous, the lower portion of the glacier, where the current is more sluggish, must increase in depth or in breadth, — or more precisely in area of cross section, — in order to enable the flood to pass.

Another agency which modifies a glacier's life also increases in power as the glacier advances, namely, the heat of the atmosphere. The lower a glacier descends the more rapidly is it melted. The gradient of its surface is thus controlled by two groups of antagonistic agencies. Decrease in flow causes the ice to increase in thickness, while melting lowers its surface. Still more complexity is apparent when one remembers that an increase of temperature is accompanied by an increased rate of flow. The records left by former alpine glaciers in Alaska show that for many miles after leaving their névés they increase in thickness, but as the effect of the increasing temperature of the lower region they invaded was felt, they gradually decreased in thickness and receded.

Returning to our imaginary glacier, we observe that in its onward march it carries the mouths of lateral valleys. If these are without glaciers, or if the ice bodies in their upper courses fail to reach the main line of drainage, an ice dam is formed in the main valley, the drainage in the lateral valleys is held in check, and lakes appear. The accumulated water may escape either over the surface of the ice dam, usually at its junction with the rocky side of the valley ; but more frequently the water disappears beneath the ice and finds its way downward through sub- or englacial tunnels. These lakes on the margin of the glacier are subject to great fluctuations on account of changes in the icy channels through which they discharge. Not infrequently they are drained suddenly, and floods occur in the valley below the end of the glacier that confined them. The empty basins refill when the outlet becomes again closed by movements in the dam of ice. Not infrequently their surfaces are whitened with floating bergs, from which boulders are scattered over the bottom. In spite of the vicissitudes that beset their lives, however, we learn by watching their basins as they are successively filled and emptied, that deposits of sand and clay are formed in them, and under favorable conditions may even fill the depressions up to the level of the wall of ice which in part forms their boundaries. Important deposits thus originate, and may remain as a part of the geological record when the glacier melts and the lakes along its margins are drained.

In our fancied study of the life of a glacier we see it approach a portion of the valley where the descent is rugged and broken. The yellow waters issuing from it are churned into foam as they leap from ledge to ledge. On reaching the place of steep descent the glacier becomes greatly broken, and for a time falls in detached masses, forming a veritable ice cascade. The precipice of rock is heightened by a wall of ice, which has a serrate crest and is broken into towers and pinnacles, separated by blue crevasses. From time to time a great tower falls with a crash, and sends a cloud of ice fragments rolling down the valley. The steep descent soon becomes blocked with fallen fragments. The face of the rocky precipice is concealed from view, except at its extremities, where it joins the sides of the valley. The broken and pinnacled ice descending the precipice is cemented together again at the bottom, and the glacier flows on, with but few scars caused by its rough passage remaining. At the ice fall the descending mass impinges with great force on the rocks at the bottom of the slope, and must there have its erosive power augmented. Rock basins worn out at such localities will be seen when the glacier retreats. The débris

carried on the glacier above where it makes its steep descent is, to a considerable extent, engulfed in crevasses, but a portion escapes these pitfalls and still darkens the surface below the cascade. A part of the stones that were engulfed soon returns to the surface, by reason of the melting of the ice; but some of them remain for a long time in an englacial or subglacial position. At each sharp descent in the bed of the glacier an ice cascade appears. When the grade is steep but not precipitous, the ice is greatly broken and presents the appearance of a rapid rather than a cascade.

The surface of the glacier throughout its lower course, and especially at its extremity, is dark with débris. The medial moraines so prominent in its middle course, and from a distance appearing like winding highways leading from the land of flowers to the land of snow, become less well defined and less definitely separated one from another. The reason for the flattening and spreading that the moraines suffer is not far to seek. Owing to the more rapid melting of the clear ice the portions protected by débris are left in relief. The medial moraines where best defined are really roof-like ridges of ice veneered with dirt and stones. From time to time a rock breaks away from its insecure position and rolls and slides down the steep slope to the clear ice below, thus tending to widen the moraine-covered tract. On gaining a new position the fallen block again protects the ice beneath and is again left in relief by the melting of the adjacent surface, and the process is repeated. The falls that the rock masses experience — and the larger ones receive the roughest treatment — result in many fractures. The blocks of stone are thus reduced in size and prepared for future usefulness in the formation of soil. Both medial and lateral moraines are broadened in this way, and in time lose their stream-like character, and the general surface of the glacier becomes covered with débris. This process is assisted also by the appearance at the surface of stones previously enclosed in the ice, but not associated with well-defined moraines.

The accidents that happen to the blocks forming surface moraines, on account of the unequal melting of the glaciers, are repeated on a smaller scale by individual blocks of stone large enough to shelter the ice on which they rest. When the conditions are favorable, such blocks of stone are raised on pedestals and form glacier tables. These growths on the glacier, like the flowers that bloom beside it, look toward the sun that gave them birth, and as they increase in height incline toward his mid-day position. Finally, they slide from their pedestals and the process is

repeated. Other features due to differential melting are also present, but belong to the minor details of the surface where waste exceeds supply, and are not conspicuous from a distance.

The glacier, now in its full strength, advances from the extremity of the valley that sheltered its youth and guided its early life, and invades the piedmont plain. The low lands are densely forested. Majestic spruce trees and aged moss-covered hemlocks stand in thick, serrate ranks across the glacier's path, but are mowed down as easily as the grass before a scythe. Crushed, broken, and splintered, the trunks are piled in huge confused heaps and overridden and buried by the slow but resistless march of the ice. Where the waters flowing from the glacier are abundantly loaded with sand and gravel, they build alluvial deposits about its margin. The streams in their passage over these alluvial cones subdivide and send off distributaries into the forest to the right and left, and the trees are surrounded and buried by sand and gravel while yet standing. A fringe of dead trees, in part denuded of their branches, marks the areas where the stream-borne deposits have made recent conquests. Under these conditions the glacier advances over the buried forests, and all vestiges of its existence are blotted out. Centuries later the still erect trunks may be revealed.

The rôle that a glacier plays in its full strength when it invades a plain or enters a broad valley may be said to depend on how well it improved the opportunities of its youth. If the débris it gathered from the amphitheatre in which it was cradled and from the cliffs that sheltered its early course is sufficiently abundant, it retains its stream-like character and builds protecting embankments along its sides as it advances. If the lateral moraines are not massive in comparison with the volume of ice, the glacier expands and forms a semicircular terminus in which a constantly increasing area of surface is exposed to the sun and rain. Radial crevasses appear in the expanding ice foot and still farther assist in its destruction.

A critical point of the life of a glacier has now been reached. Will it have strength to resist the increased warmth of the region it has invaded and continue to advance, or must it halt at an intangible boundary, where the annual melting balances the flow of ice from higher regions?

In our fancied watch we will assume that the glacier is not only unable to advance against the invisible enemies that beset its progress, but that a climatic cycle favorable to glacial growth has passed its maximum and begun to swing in the opposite direction. Some distant cause, possibly

the upheaval of a barrier in the ocean, or the slow growth of a coral reef, has deflected an ocean current that formerly bathed the adjacent coast, and the winds fail to bring as much moisture to the mountains as formerly. Perhaps the relation of the earth to the sun is undergoing a secular change, and the mean annual temperature, and the relations of the seasons, are so modified that for thousands of years conditions unfavorable to the existence of perennial snow will gradually supplant and crowd out the favorable conditions. Probably a combination of these and other changes equally gradual in their effects are at work in modifying the size and shape of the spheroid of 32°, and the snow line is rising at the rate of a few feet in a century.

The terminus of the glacier seemingly remains stationary for a time, but in reality is seldom at the same line for many successive years. Minor climatic changes experienced scores of years, or perhaps even centuries previously, at the fountains from which it flows, are transmitted like pulsations through its length, and its extremity advances or retreats a few feet in a year or in a score of years. Again, climatic changes may promote or retard melting in the glacier proper, and lead to less sluggish responses in the position of its terminus. Halts, advances, and retreats may also be caused by the concentration of débris in its wasting extremity.

The glacier has now passed its period of strength, and many changes in its appearance and in its behavior become apparent. The flow of even the most rapid threads of the current in the central part of the stream is no longer sufficient to renew the surface each year at its extremity. The terminus instead of advancing is now slowly retreating. Melting from the surface of the glacier proper is in excess of the supply of ice from higher regions, and a general shrinking and lowering of the surface is in progress. The stones and dirt previously held in the ice become more rapidly concentrated at the surface. Clear ice, especially in the lower portions of the glacier proper, is no longer visible except in crevasses. Vegetation begins to take root on the previously desolate fields of débris. A fringe of flowers and ferns soon margins the stagnant portions, and transforms them during the summer season into luxuriant gardens. The forest, previously swept away as a thing too insignificant to be worthy the attention of the legions of the ice king, re-advances year by year, and in time flourishes on the moraines resting on the ice under which relics of their ancestors lie buried. Animals wander through the forest where moss and thick undergrowths conceal pitfalls in the ice beneath, and are entrapped. Man, unattentive to the wonders about him, may tread the

silent aisles of the forest without knowing that a dead glacier lies buried beneath the carpet of vegetation on which he treads. As the ice slowly melts from beneath the forest-covered moraine, openings are formed, and lakelets surrounded with rank vegetation give variety to the scene. As these pools enlarge, the soil and boulders on their banks are undermined, and uprooted shrubs and trees fall into them. These relics of the forest, and the peaty soil formed where the depressions are partially drained, become buried in morainal débris. Many a puzzling record is thus preserved which will lead students astray in future centuries.

The forest-covered border of the fringing moraine is separated from the clear ice by broad areas of desolation, on which scarcely a lichen has taken root. On these monotonous wastes striking changes are likewise in progress. Scores and perhaps hundreds of lakes are formed, similar to those in the forest-covered moraine, but producing more apparent results, since the débris about them is not covered with a mask of vegetation. As these walls of ice about the lakelets melt, the stones and dirt on the adjacent surface are precipitated into them, and accumulate deeply over their bottom. When the general surface is lowered by melting, these deeply filled holes are transformed into prominences thickly covered with earth and stones. The irregular piles assume a pyramidal form, because of the displacement and sliding down of the rock masses on their borders. In time the sites of the basins of muddy water are marked by huge pyramids of ice, a hundred feet or more in height but concealed from sight by a veneer of stones. From our observing station, scores and hundreds of those monuments are in view. Between them are many lakelets not yet filled, and others that have been drained of their water but are yet unsightly depressions in which the stones are covered with slimy mud.

While the changes noted near the extremity of the glacier have been in progress, other signs of old age have appeared far up its course. The ice no longer fills the valley as deeply as before, but an apparent settling of its surface has occurred. The mountain slopes rising above its borders are either bare or sheathed with débris left stranded as the current subsided. The height of the ice during its maximum is marked on each side of the valley by an abandoned lateral moraine. This ridge is frequently a well-defined terrace or shelf on the steep slope. The border overlooking the valley is higher than the margin adjacent to the mountain, and forms a ridge composed of boulders and stones of many sizes and shapes. Between the ridge and the upward slope of the mountain, there is frequently a level-floored space, formed of sand and gravel

swept by torrents from the region above. Streams descending lateral gullies are deflected by the outer ridge, and, should the general grade of the valley be sufficiently gentle, may form lakelets and swamps.

The slope of the abandoned lateral moraines, or their gradient, is plainly less than the gradient of the surface of the ice still remaining in the bottom of the trough. Far down the valley, near where it opens out on the piedmont plain, their elevation may be a thousand feet above the surface to the stagnant ice, but as one traces them up stream this interval becomes less and less, until in proximity to the lower border of the mantle of perennial snow, the two coincide. This is the reverse of the process noted during the advance of the glacier, when the strong current caused the ice to thicken most rapidly at a distance below the source of supply, and shows that Summer is invading the realm of Winter.

The highest lateral moraine left stranded as the ice melts, marks the limit between the rugged and angular crags that have been long exposed to the action of frost and rain, and the surfaces which have been worn and rounded by flowing ice. Above, the lines in the sculpturing are more or less vertical, in conformity with the direction of flow of the streams and rills that made them ; below, the most pronounced elements in the relief trend in the direction of the major axis of the valley, and appear to be approximately horizontal.

Most interesting of all the records on the sides of the valley left exposed by the shrinking of the ice, but scarcely discernible from a distance, are lines and grooves on the ice-worn surfaces. When the rocks are hard and fine-grained, their polished surfaces glitter in the sunlight like burnished granite fresh from the builder's hand. A near view will generally show, however, that the tools that did the polishing were not carefully selected. The glaciated surfaces are covered by scorings of varying character, from light, delicate lines, such as might be traced with a diamond's point, up to deep grooves and heavy irregular gouges, seemingly made by huge boulders of hard rock forced along under heavy pressure. The more even lines, especially, are in parallel series and trend in the direction of ice movement. Similar markings are also to be found at the extremity of the glacier wherever its retreat has exposed the hard rocks over which it passed. A close inspection will reveal many localities where the glacial ice charged with sand and stones rests directly in contact with polished and striated surfaces. The manner in which the graving tools that made the inscriptions are held in the icy matrix is thus revealed.

As we watch the slowly receding extremity of the glacier, we note that its rate of retreat is not uniform. At times it remains practically stationary for many years, and the débris carried forward on its surface is concentrated in its extremity. When the glacier again retreats, an irregular accumulation of boulder, stone, sand, and earth, indiscriminately commingled, is left as an embankment across the valley. The crest of the ridge forms a curve concave up stream, and is apt to have its more gentle slope on the side facing the shrunken glacier. Several such crescent-shaped piles may be left as the glacier slowly retires. Many of these abandoned terminal moraines form dams above which the drainage from the glacier and from adjacent slopes is retarded, and lakes are formed. These lakes, like those originating along the sides of the glacier during its advance, are short-lived. They rise rapidly as the ice withdraws, and in fact are flooded and begin to overflow long before the retreat of the ice has allowed them to fully expand. While yet small, they are turbid with glacial silt and have a peculiar yellowish green color. When they reach a large size, their waters are more or less perfectly clarified, and may appear as a plain of blue in which the majestic mountains are mirrored. Where glacial streams enter, there is always a fringe of yellow shading off through innumerable tints to the clear blue beyond and showing that abundant sediments are there being deposited. Unfortunately, as it would seem, various agencies conspire to deface and to remove these pleasing results of glacial agencies. The lake basins are rapidly filled with sediment, and the overflowing water cuts deep channels through the unconsolidated material that holds them in check. For these reasons, they pass rapidly through their predestined changes, and finally are completely drained and their bottoms transformed into smiling meadows. Dark evergreen forests border the even meadows of waving grass, and flowers beautify their surfaces. The now sluggish streams meander in many graceful curves between banks that are outlined by the pink of budding willows in spring and with the gold of aspen leaves in autumn. Deer and other inhabitants of the region find there a sheltered retreat. The once frozen solitude is transformed into a park, more beautiful and richer in delicate charms than man has yet designed. The plowshare of ice that descended from the mountains broke the flinty rocks and prepared the land for the harvest.

While watching the transformation from stern winter to smiling summer in the lower valley, the extremity of the glacier has receded above that portion of its bed where great crevasses and ice cascades broke

its surface during its descent. At the base of these steep slopes, now worn and rounded, other lakes are born. Their cradles are hollows in the solid rock. No moraine piles hold the water in check, but the rims of their basins are polished and striated ledges. Could we see their bottom, we would find that they, also, are smoothed and rounded. As the ice withdraws from the higher portions of its bed the number of rock-enclosed tarns increases, and fresh charms are added to the diversity and beauty of the region. In neighboring valleys and adjacent slopes where the rocks are essentially the same but have not been subjected to glacial action, rock basins are absent. Evidently their abundance in the abandoned beds of the retreating glacier is the result of the abrasion that the rocks suffered from the ice that moved over them. They are plentiful where the descent is precipitous, and absent at lower levels, where the grade of the ice stream was gentle. The region where they occur is notably free from moraines and other glacial deposits ; lower down the valley where they are absent there are heavy accumulations of débris. That their rarity in the lower part of the valley is not due to the masking of the hard-rock surfaces by glacial deposits is shown by their absence from areas where such deposits are lacking. The regions where the rock basins are most abundant are regions where abrading and transporting agencies were active ; the lower portion of the valley where they do not occur are where the glacier did least work, and where deposition and not erosion was the rule. Where the glacier was heavily charged with débris it became sluggish and did but little abrading. In many instances rock-basin lakes are situated at the bottom of steep inclines, down which the ice descended and pressed with great force on the rocks where there is an abrupt changé to a more gentle grade. The rock-enclosed lakes are, in general, longer-lived than those held by moraines, but in time they too become filled with sediment and are transformed into brilliant gardens of alpine flowers.

Had our glacier advanced boldly into the piedmont plain, possibly another variety of rock basin would have been excavated, but in the fancied instances before us it is not practicable to include a complete analysis of glacial action.

The last stages in the decline and death of a glacier are slow and frequently much prolonged. The blue ice visible below the margin of the white névé contracts more and more, until during certain seasons, or for a series of years, it is completely concealed by a covering of snow. Fluctuation still occurs, however, and during years, or a succession of years, when the winter snows are light, or summer melting accelerated, the glacier

proper may be seen for a short time in late summer or early autumn. In its old age the glacier reaches a second childhood in which the characteristics of its early years again appear. So complete is this similarity in many instances that it is difficult, if not impossible, for one to decide whether a miniature glacier sheltered in the encircling arms of a mountain crest, is the beginning of a new ice extension or the remnant of a glacial epoch that has nearly passed away. The depth and character of the amphitheatre in which the snow and ice lie, and the shape and sculpturing of the valley leading from it, may furnish proof of a former period of intense glaciation. But whether in many instances the glacier that did the work was completely melted and a new period of ice extension initiated, or whether a remnant of the dying glacier still remains, I know of no test by which to decide.

Throughout the growth and decadence of the glacier we have been watching, it has been apparent that even the grandest results have been attained by slow, and as they ordinarily appear to us, imperceptible changes. More than this, the climatic variations made manifest by the behavior of a glacier do not go on continuously in one direction for long periods, but are accomplished by irregular pulsations. There have been great cycles favoring growth or decline, and within these there have been minor periods during which the changes in progress were retarded and even reversed; but the resultant of several minor periods coincided with the general change in progress.

It is safe to say that the main features in the life histories of even the greatest piedmont and continental glaciers are similar to those presented by a single ice stream of the alpine type. Even the coming and going of glacial periods are so far as one can judge in obedience to similar laws. The records left by Pleistocene ice sheets show that they underwent many fluctuations, some of which were so pronounced that they are usually considered as independent periods. One of these pulsations embraced a far greater lapse of time than the entire life history of a glacier such as has just been traced.

A wonderful vista is unfolded when one attempts to include in a single mental picture the transformations that accompany a climatic revolution so vast that a continent became buried beneath thousands of feet of ice, and on retiring left a soil in which the most advanced civilization known to history took root. Surely such a theme is worthy of being interpreted in a great poem, beside which the vision of a Dante or a Milton would be lacking in interest.

Concluding Note.

In preceding chapters I have attempted to present a review of what is known concerning the existing glaciers of North America, and have indicated in many instances where more detailed information in reference to special regions and to individual glaciers may be found. I have also ventured to point out in some cases the direction in which new explorations in this fascinating field can be most profitably undertaken. In the chapter just concluded an attempt was made to present in one view an outline of the life history of a single alpine glacier. A continuation of the studies here begun would naturally lead to a review of the records left by extinct glaciers, since in this, as in many other departments of geology and physiography, "the present is the key to the past"; but as our fireside journey over mountains and across ice fields has been long and arduous, I will, for the present, part company with the reader here.

For the benefit of the student who may desire to continue the course of reading to which this book is intended as an introduction, I would suggest the numerous memoirs on surface geology contained in the annual reports of the United States Geological Survey and in The Journal of Geology, published at the University of Chicago.

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